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Cellulosic Ethanol: Feedstocks, Conversion Technologies, Economics, and Policy Options

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Summary

In the Energy Independence and Security Act of 2007 (P.L. 110-140), Congress mandated the use of a large and rapidly increasing volume of biofuels as part of the U.S. national transportation fuel base. In particular, the share of cellulosic biofuels is mandated to grow to 16 billion gallons by 2022—a daunting challenge considering that no commercial production existed as of mid-2010. Cellulosic biofuels can be produced from almost any sort of biomass. As a result, a variety of biomass types that can be produced or collected under a range of geographic settings are potential feedstock sources. However, part of the mandate's challenge will be encouraging farmers to produce or collect non-traditional biomass materials that require multiple growing seasons to become established, and for which markets currently do not exist. Participation represents a substantial risk for producers, and even under the most optimistic conditions, U.S. agriculture will be challenged to produce the enormous volume of biomass needed to meet the biofuels mandate.

Potential biomass feedstocks are numerous and widespread throughout the United States, and include woody biomass, perennial grasses, and agricultural and forest residues. Each type of biomass faces tradeoffs in terms of production, storage, and transportation. Dedicated energy and tree crops have large up-front establishment costs and will likely take several years to produce a commercial harvest, but can produce high yields with relatively low maintenance costs thereafter. Residues are nearly costless to produce, but confront difficult collection strategies and do not always produce uniform biomass for processing. Agricultural residues face complicated trade-offs between soil nutrient loss and biomass yield, as well as questions about the optimal timing strategy for harvesting the main crop and residue (either jointly or separately). Logging residues confront a tradeoff with energy production at the plant (via burning).

None of the potential feedstocks (other than starch from corn) are economical to convert into biofuels under current commercial technology without substantial federal policy intervention. In addition to federal policy and the choice of feedstock, the processing technology used, the distribution infrastructure, and blending rates are expected to play major roles in the economic viability of cellulosic biofuels. Different processing technologies yield different biofuels in terms of energy content and usability, while also strongly influencing the economic viability of biofuels production. Ethanol produced under current biochemical processes yields only 67% of the energy of an equivalent volume of gasoline, and (due to its chemical properties) cannot use the same storage tanks, pipelines, and retail pumps as gasoline. In contrast, synthetic petroleum products (i.e., green hydrocarbons) obtained from biomass processed using more costly thermochemical technology yield an energy content nearly equal to petroleum fuels and can be used in existing fuel infrastructure. Currently ethanol is blended in most gasoline at about a 10% rate. If the rising usage mandate is to be met, the biofuels blending rate will necessarily have to increase, at which point the energy equivalence of a biofuel will likely influence the choice of processing technology, distribution infrastructure, and federal policy incentives.

Many uncertainties remain concerning biomass producer participation rates, the choice of biomass, and associated yields and costs of production, harvest, storage, and transportation, as well as contractual marketing arrangements, plant location, and conversion technology, among other issues. This report attempts to summarize the current state of knowledge regarding potential biomass feedstocks, production and marketing constraints, processing technologies, and the economics of biomass from field to fuel under current and hypothetical policy circumstances. As such, it is intended to serve as a reference for policymakers interested in understanding the complexity underlying the development of a large-scale, biomass-based fuel system.

An executive summary of the report is available in Chapter 1.

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Introduction

Under the Energy Independence and Security Act of 2007 (EISA; P.L. 110-140), Congress mandated the use of a large and rapidly increasing volume of biofuels as part of the U.S. national transportation fuel base. In particular, the share of cellulosic biofuels is mandated to grow to 16 billion gallons by 2022—a daunting challenge considering that no commercial production existed as of mid-2010. In addition to the biofuels use mandate, Congress also provides federal support in the form of tax credits to fuel blenders and biofuels producers, and an import tariff on foreign-produced ethanol to protect and encourage the development of the U.S. biofuels industry.

Despite this strong federal support, many uncertainties remain over whether a large-scale, economically viable cellulosic biofuels system can be successfully developed. These uncertainties include the following.

- Which biomass source and processing technology will provide the highest energy yields at the lowest cost?
- What incentives will encourage biomass producers to cultivate dedicated crops that may take three or more years before they are established and produce marketable output, and for which no market presently exists?
- How will large volumes of biomass—that must be produced within a narrow temperate-zone harvest window (e.g., March to October)—be harvested, dried, stored, and ultimately transported to a processing plant that must operate throughout the year?
- What changes will be needed in the U.S. transportation-fuel infrastructure to facilitate distributing and consuming the mandated rapid, large expansion of cellulosic biofuels?
- What set of federal policies can best facilitate the development of such a system?
- Will there be regional consequences within the United States from the emergence of such a system? What about potential international consequences?

It is still too early to begin to answer many of the broader social welfare questions, such as who will be potential winners and losers in the development of a large-scale biomass-based biofuels system. However, substantial research has been done in recent years concerning the economics of production, harvest, and energy yield for various biomass sources under different processing technologies. A review of this research can help to clarify current bottlenecks in the development of a cellulosic biofuels industry and provide some guidance to policymakers looking to extend or modify existing federal policy, or formulate new policy in support of such a biofuels industry.

This report attempts to summarize the current state of knowledge regarding potential biomass feedstocks, production and marketing constraints, processing technologies, and the economics of biomass from field to fuel under current and hypothetical policy circumstances. As such, it is intended to serve as a reference for policymakers interested in understanding the complexity underlying the development of a large-scale, biomass-based fuel system.

CRS has several reports addressing different aspects of the U.S. biofuels sector (including cellulosic biofuels) and related federal policy. This report is different in that it provides a broad overview of the nascent U.S. cellulosic biofuels industry and the many uncertainties associated with its future. This assessment was conducted by a team of researchers at Purdue University's Department of Agricultural Economics. The report provides a "snapshot" of current technological development, but is both prospective and retrospective because it also examines emerging or advanced technologies that may affect future biofuels development, and looks at evidence from a growing body of research on the economics of biomass production and biofuels processing as guidelines for shaping energy policy.

Structure of the Report

The report contains five chapters. The first chapter is an Executive Summary, which provides an overview of the report's main findings. The Executive Summary is followed by the main report, which consists of Chapters 2-5, organized like sections of a typical CRS report, together with figures and tables listed in the Table of Contents. Each chapter can be read independently; however, Chapters 2-4 ("Introduction," "Lingocellulosic Feedstocks," and "Cellulosic Biofuel Conversion Technologies") provide the reader with background and context for a more complete understanding of the economic analysis and discussion contained in the final chapter.

Other CRS Reports on Cellulosic Biofuels

CRS has written a suite of products on different aspects of U.S. biofuels policy in general, and cellulosic biofuels policy in particular. These products may be accessed through the CRS online "Issues in Focus/Agriculture/Agriculture-Based Biofuels" website, and include the following reports:

- CRS Report R41282, *Agriculture-Based Biofuels: Overview and Emerging Issues*, by Randy Schnepf
- CRS Report RL34738, *Cellulosic Biofuels: Analysis of Policy Issues for Congress*, by Kelsi Bracmort et al.
- CRS Report R40529, *Biomass: Comparison of Definitions in Legislation Through the 111th Congress*, by Kelsi Bracmort and Ross W. Gorte
- CRS Report R40155, *Renewable Fuel Standard (RFS): Overview and Issues*, by Randy Schnepf and Brent D. Yacobucci
- CRS Report R41106, *Meeting the Renewable Fuel Standard (RFS) Mandate for Cellulosic Biofuels: Questions and Answers*, by Kelsi Bracmort
- CRS Report RS22870, *Waiver Authority Under the Renewable Fuel Standard (RFS)*, by Brent D. Yacobucci
- CRS Report R40110, *Biofuels Incentives: A Summary of Federal Programs*, by Brent D. Yacobucci
- CRS Report RL34239, *Biofuels Provisions in the 2007 Energy Bill and the 2008 Farm Bill: A Side-by-Side Comparison*, by Randy Schnepf and Brent D. Yacobucci
- CRS Report R41296, *Biomass Crop Assistance Program (BCAP): Status and Issues*, by Megan Stubbs
- CRS Report R40445, *Intermediate-Level Blends of Ethanol in Gasoline, and the Ethanol "Blend Wall"*, by Brent D. Yacobucci
- CRS Report R40460, *Calculation of Lifecycle Greenhouse Gas Emissions for the Renewable Fuel Standard (RFS)*, by Brent D. Yacobucci and Kelsi Bracmort

Report Authorship

This technology assessment and report was written by Purdue University, Department of Agricultural Economics, under the leadership of Wallace E. Tyner,[1] together with Sarah Brechbill[2] and David Perkis.[3] The report's authorship rests with Tyner, Brechbill, and Perkis.[4] The work was performed under contract to CRS, and is part of a multiyear CRS project to examine different aspects of U.S. energy policy. This report was funded, in part, by a grant from the Joyce Foundation. Randy Schnepf served as the CRS project coordinator.

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Chapter 1: Executive Summary

Cellulosic Biofuels

Cellulose-based biofuels are thought to offer substantial advantages over current corn ethanol, foremost that they can be grown at low cost on marginal land where they will not compete with traditional food crops. In addition, cellulosic biomass sources are abundant and widely distributed throughout the United States.

Changes made in the U.S. Renewable Fuel Standard (RFS) in 2007 require renewable fuels use of 36 billion gallons by 2022, more than triple the nearly 11 billion gallons consumed in the United States in 2009. A substantial portion (16 billion gallons) of the 2022 RFS is required to come from cellulosic biofuels, an industry in its infancy and not yet economically viable. Considerable uncertainty remains about how a cellulosic biofuels industry will evolve, what infrastructure changes will be needed to support this development, and how the development of a biomass-based biofuels industry will alter regional economic and environmental circumstances within the United States.

The major objective of this report is to summarize what is and is not known about cellulosic biofuels. What do we know about the technical and economic potential of the various feedstocks and conversion processes? What are the key bottlenecks or impediments to the development of a cellulosic biofuels industry? What are the likely impacts of the government mandates and incentives related to cellulosic biofuels? This paper attempts to answer these questions based on published literature and model simulations.

The Choice of Feedstock

Current research on feedstocks focuses on maximizing yields, harvesting and collecting efficiently, and testing various supply chains to minimize losses and overall delivered costs.

Feedstock characteristics. The preferred biomass feedstocks, known as lignocellulosic feedstocks, are composed of three main parts: cellulose, hemicellulose, and lignin. The different concentrations of these components in particular feedstocks will affect the efficacy of the conversion technology. Feedstocks with larger quantities of cellulose and hemicellulose are favored in biochemical conversion processes as the conversion technology stands presently, but research is being conducted to incorporate lignin into conversion or modify some of its properties through hybrid feedstocks. As a result, research offers the potential to alter the viability and preference of various feedstocks.

Feedstock sources. Potential biomass feedstocks are numerous and widespread throughout the United States, and include agricultural residues from such crops as corn, wheat, rice, and sugarcane, perennial grasses such as switchgrass and *Miscanthus*, short-rotation woody crops such as poplar and willow, and forest residues removed directly from the forest or taken from mills after processing. In 2010, the Environmental Protection Agency estimated that the 16 billion gallons of cellulosic biofuels mandated by the RFS for 2022 will be derived from dedicated energy crops (49.4%), agricultural residues (35.6%), urban waste (14.4%), and forest residue (0.6%). Several studies based on agronomically viable U.S. biomass production suggest that the biofuels potential is significantly larger than 16 billion gallons.

Feedstock production and harvest costs. Each type of biomass faces tradeoffs in terms of production, storage, and transportation. Dedicated energy and tree crops have large up-front establishment costs and may take several years to produce a commercial harvest, but can produce high yields with relatively low maintenance costs thereafter. Residues are nearly costless to produce, but confront difficult collection strategies and do not always produce uniform biomass for processing. Agricultural residues also face complicated trade-offs between soil nutrient loss and biomass yield, as well as questions about the optimal timing strategy for harvesting the main crop and the residue (either jointly or separately). Logging residues confront both a tradeoff with energy production at the plant (via burning) and a uniformity of quality issue for processing.

Producer participation. A key aspect of biomass production will be understanding what economic incentives will encourage producer participation in growing and/or collecting biomass feedstocks. Whether the feedstock is a residue or dedicated crop, there is not much experience among producers, markets do not presently exist for most potential biomass crops, and few risk management tools (e.g., crop insurance) are available to producers. Studies presently use a wide range of estimated participation—30% to 80%—depending on the size and location of the processing plant, the price being paid for biomass by the plant, the cost of producing, harvesting, and collecting biomass for a producer of a given size, and the terms of producer contracts.

Feedstock transportation. From the perspective of the biofuels processing plant, the choice of which feedstock to use will depend on the location of the plant and the local feedstock supply availability. Agricultural residues and perennial grass feedstocks have relatively low energy density, which means a large volume would be needed by a plant to meet demand. As a result, transportation costs may be crucial in the biomass choice. For example, a 50-million-gallon-per-year cellulosic ethanol plant (that converts a ton of corn stover—which includes the stalks, leaves, and cobs of the corn plant—into 90 gallons of biofuel) would need over 550,000 tons of corn stover harvested from roughly 280,000 acres of land (assuming 2 tons per acre of removable corn stover) in order to stay operational for a year. Because trucks become physically full when hauling biomass before reaching their weight limits, more truckloads would be required for cellulosic biofuel production relative to corn-based ethanol, thus making the per-unit transport cost much higher for cellulosic feedstocks than for corn. The greater number of trucks required to transport cellulosic feedstocks might also impose a heavy burden on rural transportation infrastructure. Compacting the biomass prior to transport may result in net savings if transport cost savings offset densification costs.

Feedstock storage. Because the harvest of dedicated energy crops and agricultural residue is concentrated during one part of the year, long-term storage will be needed to hold the biomass until the plant is ready to use it (keeping in mind that biofuels plants are designed to run year-round). For plants that can eventually use multiple feedstocks, they will be able to use fall-harvested biomass around the time it is harvested, followed by perennial grasses with their wider harvest period, or woody biomass or urban waste that can become available throughout the year. Storage costs, inclusive of biomass dry-matter loss due to weathering and exposure, could be crucial in determining optimal feedstock sources in certain agro-climatic zones.

Uniformity of feedstock. Biomass can have highly inconsistent quality and characteristics, not only among feedstocks but within a feedstock type. Delivering a uniform feedstock to the plant will decrease processing and pretreatment costs. Plants receiving biomass that has been harvested differently and stored under a variety of conditions will incur additional costs to arrive at a uniform feedstock product. With more experience and the development of the appropriate harvesting, collecting, and storage technologies, both standardization and densification of biomass could take place before the biomass even arrives at the plant, which would lower per-unit transportation costs and allow the plant to start with a uniform and consistent product, regardless of its source.

The Choice of Processing Technology

Two primary biomass-to-biofuel conversion methods for lignocellulosic feedstocks are currently under consideration for commercial use—biochemical conversion and thermochemical conversion. Energy yields and production costs for each process may vary substantially based on the specific implementation design and feedstock.

Biochemical Conversion

Process. The biochemical conversion process is similar to the process currently used to produce ethanol from corn starch. Enzymes or acids are used to break down a plant's cellulose into sugars, which are then fermented into liquid fuel. Four key steps are involved. First, feedstock is pretreated by changing its chemical makeup to separate the cellulose and hemicellulose from the lignin in order to maximize the amount of available sugar. Second, hydrolysis uses enzymes or acids to break down the complex chains of sugar molecules into simple sugars for fermentation. Third, fermentation is used to convert the sugar into liquid fuel. Fourth, the liquid fuel is distilled to achieve a 95% pure form.

Production costs. Each step of the conversion process incurs costs. A key cost of *pretreatment* is the time incurred. Biological pretreatment, using fungi, for example, can take 10 to 14 days. Chemical pretreatment may be faster but with higher costs for chemicals. *Hydrolysis* cost depends largely on the cost of enzymes, which has been estimated at $0.50 per gallon. However, hydrolysis may require different enzymes for different parts of the plant, thus incurring varying enzyme costs for different feedstocks. The effectiveness of hydrolysis is highly dependent on the effectiveness of pretreatment—too much lignin remaining after pretreatment will impede enzyme efficiency. More accessible sugar (following efficient pretreatment) may improve enzyme function at lower costs. Regarding *fermentation*, different sugar types, for example, hexoses (six-carbon sugars) or pentoses (five-carbon sugars), may require different yeast strains for fermentation. Improved yeast strains that ferment various sugars could lower production costs. Some cost savings may be available through management of *recovered lignin*, which can be burned to generate electricity and steam to power the bio-refinery or for other outside uses. Primary research areas for potential improvement in energy yield and cost reduction are in pretreatment, hydrolysis, and fermentation. Distillation is already a well-established technology. Successful improvements should make the process adaptable to multiple feedstocks.

Energy equivalency. The biochemical conversion of biomass into alcohol produces a liquid fuel (i.e., ethanol) that contains only about 67% of the energy content of gasoline. When ethanol is blended with gasoline at low rates (e.g., 10% or less), the reduced gas mileage resulting from the blended fuel is sufficiently small that most consumers are likely to treat the blended fuel as equivalent volumetrically (i.e., gallon for gallon) with gasoline. However, at higher blend rates, especially at an 85%-ethanol blend rate (E85), the lower mileage is more noticeable and consumers may prefer energy-equivalent pricing, whereby the price for a gallon of E85 should be only 72% of the price of a gallon of gasoline.

Petroleum infrastructure equivalency. Because of its physical properties, ethanol cannot be used in the same infrastructure (e.g., pipelines, storage tanks, service pumps) used to deliver retail gasoline. Nor can it be used directly by standard vehicle systems that have not been adjusted for ethanol blends greater than 10% (or 15% for model year 2007 or newer light-duty vehicles). This both limits ethanol retail delivery opportunities and raises the cost of delivery.

Thermochemical Conversion

Process. Thermochemical conversion processes, which use heat to decompose the feedstock, are well established and developed. Unlike biochemical conversion, thermochemical conversion uses the entire biomass, including the lignin portion. There are two main types of thermochemical conversion processes—gasification and pyrolysis.

Gasification is an anaerobic process where the partial combustion of biomass feedstock at over 700°C generates synthesis gas, or syngas, a mixture of carbon monoxide and hydrogen. The syngas must be cleaned of tar, ash, and other impurities prior to the next processing step. The Fischer-Tropsch process is then used to convert the "cleaned" syngas into a variety of liquid fuels. The presence of impurities in syngas might disrupt the Fischer-Tropsch process by inactivating the catalyst. Also, prior to gasification, the biomass must have 20% or less moisture. For practically any type of biomass, drying will be required. Established drying technologies usually take place at high temperatures, which creates an opportunity for improvement. Gasification is prohibitively expensive and would only be used commercially at extremely high gasoline prices.

Pyrolysis is the partial combustion of biomass feedstock at 450°C to 600°C in the presence of no oxygen, which produces bio-oil. Bio-oil, which is rich in carbon, is similar to crude oil and must be refined into biofuels. Fast pyrolysis requires higher temperatures than slow pyrolysis but occurs in about two seconds. Currently, fast pyrolysis is receiving the most attention as a viable conversion process. Keeping the pyrolysis oil stable long enough to transform the bio-oil into hydrocarbons is one of the major barriers in the pyrolysis pathway. Because pyrolysis converts the biomass into a liquid form, it is easier to store and transport.

Energy and infrastructure equivalency. The thermochemical conversion of biomass into synthetic fuels (or green hydrocarbons) produces liquid fuels that are essentially energy-equivalent to their petroleum counterparts, and fully adaptable for use in existing petroleum fuel infrastructure. As a result, energy-equivalent pricing favors thermochemically processed biofuels over biochemically processed biofuels.

Research keys. With respect to gasification, research is being done to dry biomass at lower temperatures and use excess heat from drying for other purposes. With respect to pyrolysis, stability of bio-oil and general cost reductions are the major research issues.

Commercialization Status

Neither conversion process is ready for commercialization. Presently, most cellulosic biofuels production is taking place in laboratories and small-scale demonstration and pilot plants. Plans for commercial plants have been announced by several companies, but development is likely to be slow, absent significant incentives. Substantial cost reductions will be necessary for successful commercial development. Several processes are currently being researched and developed in laboratories, but it is difficult to know with any certainty whether those that appear successful in trials will also be successful on a commercial scale. Given the lack of commercial production to date, per-gallon cost estimates for cellulosic biofuels are highly uncertain, but estimates based on laboratory and pilot plant results range from $2.50 per gallon to slightly over $3.00 per gallon.

The Department of Energy Biomass Program's Theoretical Ethanol Yield Calculator calculates the maximum theoretical biofuel yield per ton of feedstock with biochemical conversion of feedstocks based on their composition. Based on its results, the theoretical yields for corn stover, switchgrass, and forest thinning are 113, 97, and 82 gallons per dry ton, respectively. As plants and technologies approach commercialization, the rate of efficiency could approach 100% of the maximum theoretical energy yield.

Economic Comparison of Biomass, Processing Technology, and Policy Choices

Current biofuels production technologies (biochemical and thermochemical) were analyzed under the market conditions that prevailed during mid-2010, using a deterministic simulation model (with and without the tax credit subsidy).

Under *volumetric pricing*, with the current ethanol tax credit of $0.45 per gallon, the average corn-ethanol plant breaks even (operates at zero profit) when the price of oil is $56.33 per barrel (and the stochastically modeled corn price is $3.41 per bushel). In other words, the tax credit allows ethanol plants to operate profitably whenever oil prices are $56.33 per barrel or higher. Without the ethanol tax credit, the breakeven price of oil rises to $71.45 per barrel (still below recent market prices). Higher oil prices are needed to offset higher corn prices. The breakeven oil price scenarios are substantially higher for cellulosic biofuels—even with a much higher tax credit of $1.01 per gallon, whether produced from biochemical or thermochemical processes ($92.74 and $113.77, respectively, with tax credit).

Under *energy-equivalent pricing*, the breakeven oil price for corn ethanol rises considerably—$91.62 with the tax credit, and $114.19 without the tax credit—as the consumer has to spend more money to obtain the same energy (or mileage) available from petroleum fuels. The breakeven oil price is prohibitive for biochemical cellulosic biofuels ($145.98 with subsidy; $196.64 without). However, because its energy yield is nearly equal to fossil fuels, thermochemical biofuels appear more competitive ($98.92 with subsidy; $143.92 without).

Simulation results suggest that corn ethanol is profitable only if based on volumetric pricing as compared to energy-equivalent pricing. Biomass-based cellulosic biofuels are not yet profitable under either pricing approach (volumetric or energy-equivalent), even with a much higher tax credit of $1.01 per gallon. Currently, the *fixed tax credit* ($0.45 per gallon) incentivizes biofuels production during periods of low petroleum fuel prices; however, during periods of high oil prices (when biofuels are inherently more competitive with fossil fuels), the fixed subsidy adds to plant profitability at taxpayers' expense while encouraging greater biofuels production than is sought by the marketplace. A *variable subsidy* that declines with higher oil prices has been proposed as a policy tool to maintain biofuels incentives while limiting taxpayer exposure. This report includes a comparative analysis of a fixed versus variable tax credit, not as a policy recommendation, but strictly as a comparative analysis to aid Congress's understanding of the differences between the two policy options. Model results found that the variable subsidy lowered producer risk and taxpayer costs relative to the fixed subsidy, but had slightly lower average returns—largely because subsidy payments were not made at high oil prices.

Chapter 2: Introduction

The major objective of this paper is to summarize what is and is not known about cellulosic biofuels. For years cellulose-based biofuels have been touted as the future of bioenergy. What is the situation today? What do we know about the technical and economic potential of the various feedstocks and conversion processes? What are the likely impacts of the government mandates and incentives related to cellulosic biofuels? This report attempts to answer these questions based on published literature and model simulations.

Recent changes in the Renewable Fuel Standard (RFS) in the United States will require renewable fuels production to more than triple in the next 12 years (by 2022), and those increases are expected to come largely from cellulosic biofuels, an industry in its infancy and not yet economically viable.[5] Cellulosic feedstocks of interest include agricultural residues from such crops as corn, wheat, rice, and sugarcane, perennial grasses such as switchgrass and *Miscanthus*, short-rotation woody crops such as poplar and willow, and forest residues removed directly from the forest or taken from mills after processing, just to name a few. Current research on feedstocks focuses on maximizing yields, harvesting and collecting efficiently, and testing various supply chains to minimize losses and overall delivered costs (**Figure 1**). Cellulosic conversion technologies are not the same as for corn ethanol, as this biomass material is much more complicated than starch-based feedstocks.[6] Conversion technologies receiving the most attention include the biochemical and the thermochemical approaches. These technologies are not completely new, but their previous applications differ greatly from cellulosic biofuels.

Figure 1. Cellulosic Ethanol Supply Chain

Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels and Advanced Vehicles Data Center, 2009, at http://www.afdc.energy.gov/afdc/ethanol/basics.html.

With both the supply of feedstocks and conversion technologies still in the early stages of development and neither having yet arrived at a commercial scale, future progress in both areas is uncertain. It remains to be seen whether the development of one will come to dominate the development of the other, or whether the two can evolve simultaneously while still arriving at a workable outcome to fulfill the advanced biofuels requirements of the RFS.[7] The primary theme for both feedstocks and conversion technologies is cost reduction in order to make commercialization a reality and to make cellulosic biofuels competitive with other energy sources. Research and development must make cellulosic biofuels production as flexible as possible in order to accommodate future improvements. Governments and universities will play an important role in reducing risk and providing guidance as feedstock producers and biofuels plants break ground on cellulosic biofuels production.

This report focuses on feedstock production, feedstock logistics, and biofuel production; however, challenges and obstacles to the distribution infrastructure and end use of biofuels in vehicles are also discussed. The remainder of the report is divided into three sections.

The first section (“Chapter 3: Lignocellulosic Feedstocks”) covers the various types of lignocellulosic feedstocks, their respective characteristics, and a brief summary of how each feedstock is established and maintained. Then yields and production costs are outlined from a variety of studies to show the potential market effect of location, input costs, and assumptions.

[5] J. W. Kram, “Building Blocks to Biofuels Success,” *Ethanol Producer Magazine*, December 2008.

[6] E. Petiot, “The Important Role of Enzymes in Cellulosic Ethanol,” *Ethanol Producer Magazine*, November 2008.

[7] For more information see CRS Report R40155, *Renewable Fuel Standard (RFS): Overview and Issues*, by Randy Schnepf and Brent D. Yacobucci.

Next is a discussion of supply logistics and the challenges this new type of feedstock presents with respect to storage, quality, and transportation.

The second section of the report ("Chapter 4: Cellulosic Biofuel Conversion Technologies") considers biochemical and thermochemical conversion technologies. After a summary of each of the processes, the expected and theoretical energy yields of each technology are outlined. A summary of current estimates of capital and operating costs for each technology allows for discussion of where potential cost reductions might be made. Finally, a current list of planned and proposed pilot and demonstration plants is presented, with a discussion of how funding from the Department of Energy has been allocated so far.

The final section of the report ("Chapter 5: Economics and Policy of Cellulosic Biofuels") discusses the current status of relevant biofuels policy and some of the potential future policy options related to cellulosic biofuels. It also analyzes the effects of changes in these policies on the economics of cellulosic biofuel production. In particular, a simulation model is used to compare the market effects of a fixed subsidy (representative of the current fixed tax credit subsidy) and a variable subsidy that declines to zero as oil prices rise to a threshold level.

Chapter 3: Lignocellulosic Feedstocks

Lignocellulosic feedstocks are composed of three main parts: cellulose, hemicellulose, and lignin. Depending on the conversion process used, the concentration of these components in a particular feedstock will affect the efficacy of biofuel production. Cellulose is a sugar polymer chain of glucose, or six carbon sugars. Hemicellulose is a sugar polymer chain of xylose, or five carbon sugars. Lignin forms the hard plant cell walls and cannot be fermented into liquid fuels in a biochemical conversion process, as can cellulose and hemicellulose. Lignin, however, can be utilized in the thermochemical conversion process and serves as a byproduct in the biochemical conversion process useful for providing energy to power the plant and even for generating electricity. The characteristics of the different parts of biomass and the amount of each present in a particular feedstock play a role in determining the efficacy of conversion technologies. The remainder of this chapter will discuss the production, yields, costs, and supply of the major lignocellulosic feedstocks in the United States—agricultural residues, perennial grasses, forest residues, and short-rotation woody crops.

Feedstock Types

Table 1 gives estimates of the composition of some feedstocks of interest. Feedstocks with larger quantities of cellulose and hemicelluloses are favored in biochemical conversion processes as the conversion technology stands presently, but research is being conducted to incorporate lignin into conversion or modify some of its properties through hybrid feedstocks. As a result, research offers the potential to alter the viability and preference of various feedstocks.

In addition to cellulose, hemicellulose, and lignin, lignocellulosic feedstocks also include organic acids, ash, proteins, oils, minerals, and other compounds.[8] **Figure 2** uses the composition estimates from **Table 1** to determine the average composition of corn stover, switchgrass, *Miscanthus*, and hardwoods. Examples of biomass resources include the following.

- Agricultural crop residues (corn, wheat, rice, etc.)
- Perennial grasses (switchgrass, *Miscanthus*)
- Short-rotation woody crops (poplar, willow, eucalyptus)
- Conventional logging residues, wood processing mills residues, and removal of excess wood from forestlands
- Manure
- Food/feed processing residues
- Municipal solid waste and urban wood waste

Table 1. Estimated Composition of Lignocellulosic Feedstocks

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Source (Year)
Corn stover	35	28	16-21	Scurlock (undated)[a]

[8] North Central Sun Grant Center, *Composition of Herbaceous Biomass Feedstocks*, Sun Grant Initiative—North Central Center, South Dakota State University (Brookings, SD), June 2007, hereafter referred to as NC Sun Grant Center (2007); S. R. Bull, U.S. Department of Energy, Biofuels Research Program, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 13(4), 1991, pp. 443-442, hereafter referred to as Bull (1991); and N. S. Mosier, "Bioprocess Engineering for Biofuels: Pretreatment and Hydrolysis," Second Generation Biofuels Symposium 2009, Purdue University, West Lafayette, IN, 2009.

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Source (Year)
	38	26	19	NC Sun Grant Center (2007)[b]
	32	44	13	Bull (1991)[c]
	31	19	18	Bransby (2007)[d]
Hardwood	45	30	20	Scurlock (undated)[a]
	38-50	25-35	15-25	Taylor (2009)[e]
	45	19	26	Hamelinck et al. (2003)[f]
Wheat straw	38	29	15	NC Sun Grant Center (2007)[b]
	38	36	16	Bull (1991)[c]
Softwood	42	21	26	Scurlock (undated)[a]
	50	23	22	Bull (1991)[c]
	41	18	28	Bransby (2007)[d]
Herbaceous energy crops	45	30	15	Bull (1991)[c]
Switchgrass	44-51	42-50	13-20	Scurlock (undated)[a]
	37	29	19	NC Sun Grant Center (2007)[b]
	31	24	18	Bransby (2007)[d]
	32	25	18	Hamelinck et al. (2003)[f]
Miscanthus	44	24	17	Scurlock (undated)[a]
	43	24	19	NC Sun Grant Center (2007)[b]

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from sources listed.

a. J. Scurlock, "Bioenergy Feedstock Characteristics," *Biomass Basics: Fact Sheets*, Oak Ridge National Laboratory (Oak Ridge, TN), undated.

b. North Central Sun Grant Center, *Composition of Herbaceous Biomass Feedstocks*, Sun Grant Initiative—North Central Center, South Dakota State University (Brookings, SD), June 2007.

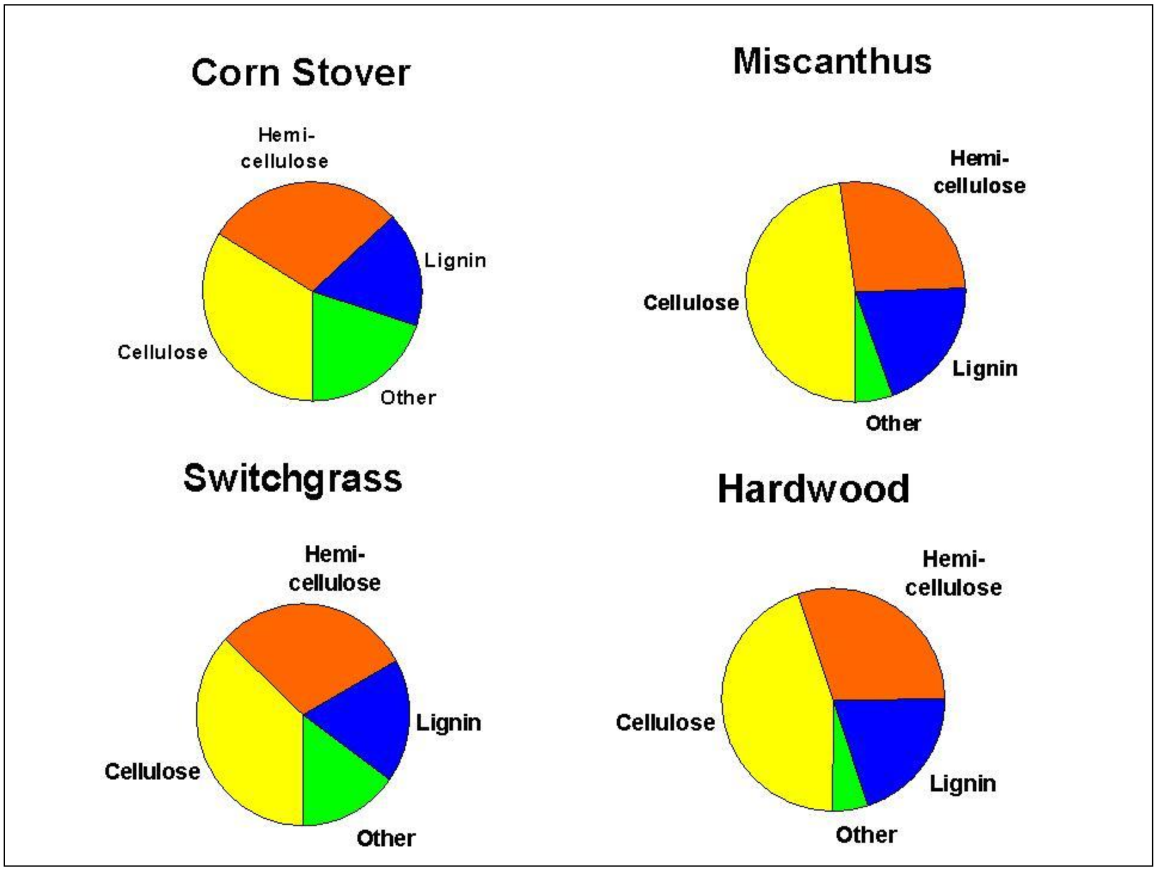
c. S. R. Bull, U.S. Department of Energy, Biofuels Research Program, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 13(4), 1991, pp. 443-442.

d. D. I. Bransby, *Cellulosic Biofuel Technologies*, "Alternative Transportation Fuels Program," Alabama Department of Economic and Community Affairs (Montgomery, AL), February 2007.

e. E. L. Taylor, "Co-products and By-products of Woody Biorefinery Processing," *Transition to a Bio Economy: The Role of Extension in Energy,* Farm Foundation Conference (Little Rock, AR), 2009.

f. C. N. Hamelinck, G. van Hooijdonk, and A. P. C. Faaij, *Prospects for ethanol from lignocellulosic biomass: techno-economic performance as development progresses*, Report NWS-E-2003-55, Utrecht University and Copernicus Institute (Utrecht, Netherlands), 2003.

Figure 2. Composition of Lignocellulosic Feedstocks by Type



Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Note: "Other" includes organic acids, ash, proteins, oils, minerals, and other compounds. Each pie chart is constructed from the simple average of the different estimates in **Table 1**.

Dedicated Energy Crops

Perennial grasses, including switchgrass and *Miscanthus*, have high yields (especially in warmer areas with a longer growing season), are low-maintenance, and have a more positive environmental impact than producing ethanol from corn. However, perennial grasses are not currently being grown on a widespread basis. Unlike residues left after the harvest of a primary commercial crop, grasses themselves are primary crops that require a relatively long-term commitment of resources to growing a crop that remains relatively obscure. As a primary crop used for energy production, and unlike residues used for energy production, perennial grasses are the only source of revenue on a given area of land. Mistakes with establishment and maintenance serve to deplete potential profits. There is no commodity market to guarantee the price of perennial grasses or to allow producers to sell their product freely. The development of contracts between producers and processing plants will prove particularly important for perennial grasses grown as primary crops with no market.

As of October 2010, there was no crop insurance available for perennial grasses, and this was thought to be a potential problem for new growers.[9] Crop insurance programs for perennial

[9] For a complete list of crop insurance programs, see "2010 County Crop Programs," Risk Management Agency,

grasses will only be developed once a base of acreage is planted, but many producers may be reluctant to plant perennial grasses in the absence of crop insurance.[10] Switchgrass is currently being grown by the University of Tennessee Biofuels Initiative and by the Oklahoma Bioenergy Center. In Tennessee, 725 acres of switchgrass were planted during spring 2008 and an additional 1,900 acres were planted during spring 2009.[11] Producers accepted into the program are paid at a rate of $450 per acre of switchgrass per year for a three-year contract. An additional 3,000 acres were expected to be planted in 2010. In Oklahoma, 1,100 acres of switchgrass were planted in spring 2008, with 1,000 acres in a single tract of land, which is the largest area of switchgrass planting in the world.[12]

A stand of switchgrass will grow annually for 10 years, while a stand of *Miscanthus* may grow annually for 15 to 20 years.[13] Perennial grasses must first be established and may not be harvested during the first year. It may also take a few harvests before the grasses reach their peak yields. Deep roots help the plant store resources from year to year, which reduce necessary fertilizer inputs. Perennial grasses are also able to take advantage of long growing seasons. This is because planting and germination do not take place annually and the plants are above the ground and taking in sun for more days starting in the spring and going until early fall.

Due to their nutrient storage ability, these grasses can be grown on marginal cropland that is often considered unfit for growing corn or soybeans. However, simply because these grasses will grow on marginal land does not mean that they will yield well, and lower yields will ultimately increase the production cost per ton. Recent studies from the University of Tennessee arrived at contrary conclusions on this matter, with one finding that a biofuels processing plant would look for switchgrass from more productive soil types in order to minimize delivered costs, while the other found that producers would choose to plant switchgrass on less productive soils, since more productive soils are reserved for corn production.[14] This contrast reflects the differences in objectives from the perspectives of producers and biofuels processing plants.

Most early *Miscanthus* research has taken place in Europe, but some research plots are now being grown in the United States. *Miscanthus* is expected to yield well in the same locations where switchgrass yields well. However, field experiments in Illinois and Iowa conducted thus far indicate that switchgrass yields can be as little as one-fourth of *Miscanthus* yields.[15] *Miscanthus* yields are higher than switchgrass yields due to their larger mass, taller height, and longer growing season. Yields for both switchgrass and *Miscanthus* are high relative to agricultural residues. This higher yield serves to decrease the production cost per ton, but perennial grasses are still more costly to produce than residues, because they are dedicated crops that must be established and maintained. Current estimates for yields tend to be reported from small-scale research trials, where establishment may be more likely to succeed within the first year and allow for a first-year cutting. It is uncertain whether perennial grass yields will be as high once it is

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USDA, at http://www.rma.usda.gov/data/cropprograms.html.

[10] R. C. Christiansen, "The Cellulosic Ceiling," *Ethanol Producer Magazine*, August 2009.
[11] S. R. Schill, "Cobs to Switchgrass to Gasoline Parity," *Ethanol Producer Magazine*, June 2009.
[12] S. R. Schill, "Oklahoma seeds 1,000 acres of switchgrass," *Biomass Magazine*, July 2008.
[13] L. Gibson and S. Barnhart, "Switchgrass," University Extension, Iowa State University, 2007, hereafter referred to as Gibson and Barnhart (2007); and M. Khanna, "Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?" *Choices* 23(3), 2008, pp. 16-21, hereafter referred to as Khanna (2008).
[14] J. A. Larson and B. C. English. "Risk Management for Energy Investments: Agricultural Policy and Extension Recommendations," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009, hereafter referred to as Larson and English (2009).
[15] Khanna (2008).

grown commercially by producers with limited switchgrass production experience.[16] Switchgrass is planted as a seed, while the most productive variety of *Miscanthus* does not produce seeds and must be planted as rhizomes, which makes establishment costs much higher. *Miscanthus* will also require more machine power to harvest because the quantity of biomass per acre is so much larger than with switchgrass. Despite establishment and harvesting costs being higher for *Miscanthus*, high yields allow those costs to be spread out over more tons of biomass per acre than switchgrass, which serves to lower the production cost per ton of *Miscanthus.* Further discussion of yields and production costs are in the sections that follow.

In the United States, perennial grasses could likely be grown on land that is currently not in use or is part of the Conservation Reserve Program (CRP), which protects land from erosion and environmental damage by maintaining vegetative cover such as native grasses.[17] For grasses, in particular, to be a viable feedstock for cellulosic biofuels, producers of these fairly uncommon crops will need to assume the risk of growing a long-run crop with high upfront establishment costs and possibly having to replant. Studies have found that switchgrass must be replanted 23% to 25% of the time due to seed dormancy and mistakes with establishment,[18] in which case establishment costs would increase substantially and overall per ton production costs would increase. Risk associated with high upfront establishment costs may be addressed through government grants to help with establishment costs, university planting programs that provide funding and expertise regarding planting and maintenance, or contracts with area cellulosic biofuels plants to supply biomass. The profitability of these relatively unknown crops in large-scale production, the profitability of other crops that could be grown in place of perennial grasses, and the proximity of production facilities will be important in determining the extent to which they are planted. Many producers who will enter into contracts with plants may be small and/or part-time operators who may lack the education, expertise, and equipment necessary to establish and maintain a perennial grass stand in a cost-effective manner. These producers may also be growing the grasses on small and dispersed fields, which will make management more expensive and less efficient. It is expected that land grant university extension programs will play a role in helping producers streamline and perfect the growing process once commercial production becomes more common.[19]

Agricultural Residues

Agricultural residues, such as corn stover, which includes the stalks, leaves, and cobs, are the by-products left after harvest of crops already being planted. Residues are more readily available than perennial grasses, which need to be established, and are typically put forth as a less expensive feedstock option, because their establishment cost is attributed to the initial crop. Instead, the primary costs associated with residues are nutrient replacement, harvesting, storage, and transportation. For the purposes of this discussion, corn stover will be used as the primary residue.

Crop residues serve to prevent erosion and nutrient loss while a field is fallow, and excess removal of residue can compromise that protection and reduce soil organic matter. The

[16] Gibson and Barnhart (2007); D. I. Bransby, *Switchgrass Profile*, Oak Ridge National Laboratory (Oak Ridge, TN), 1999; and C. D. Garland, *Growing and Harvesting Switchgrass for Ethanol Production in Tennessee*, University of Tennessee Biofuels Initiative, Univ. of Tennessee (Knoxville, TN), 2008, hereafter referred to as Garland (2008).
[17] CRS Report RS21613, *Conservation Reserve Program: Status and Current Issues*, by Tadlock Cowan.
[18] Larson and English (2009); and M. Duffy, *Estimated Costs for Production, Storage, and Transportation of Switchgrass*, A1-22, Iowa State Univ. (ISU) Extension, ISU (Ames, IA), 2008, hereafter referred to as Duffy (2008).
[19] Larson and English (2009).

appropriate amount to remove will depend on tillage practices, crop rotation, soil type, and topography. Extensive literature exists regarding the effect of residue removal on the health of the soil. Generally, more residue removal is thought to reduce organic matter and leave the soil susceptible to erosion. However, no one conclusion has been reached on the maximum amount that can safely be removed.[20] In fact, with increasing corn yields and residues roughly equal in weight to corn, some have argued that residue removal may be necessary as residue amounts increase. The amount of residue removed will depend, in large part, on the equipment used to remove it. For example, if conventional hay equipment is used, the amount of residue removed can vary depending on the number of passes. Baling alone will collect about 38% of residue, raking and baling will collect about 52.5% of residue, and shredding, raking, and baling could collect 70% of residue.[21]

Work remains to find the most efficient residue collection technique. For example, making multiple passes through the field—first to harvest the main crop, then to shred, rake, bale, and collect the residue—will increase the cost of collecting the residue and increase soil compaction in the field. In contrast, a single-pass system that performs several functions simultaneously may be overly slow to collect the principal crop and may run the risk of unanticipated inclement harvest-time weather. More efficient collection technologies will be capital-intensive and will likely be adopted by larger producers, which will leave smaller producers to use existing hay equipment or hire a custom operator to harvest residues.

Time is a critical factor for farmers in the fall harvest period. Harvest of residues must take place within a fairly small window after corn has been harvested and will be highly dependent on weather conditions. The top priority of producers will certainly be the corn crop, and if removing residue puts their corn yield at risk, producers may be reluctant to agree to remove it.

A one-pass harvest system that attaches to the combine appears to be the next step in equipment development for residue harvest if it can be done without slowing down the harvest. Hay equipment is available but is less efficient, and equipment that will only collect residues may not appear for another 15 to 20 years.[22] Current research at Iowa State University is developing a one-pass harvesting system that attaches to a conventional combine as a modified header in the front and a chopper and blower in the back. This was preferred to a one-pass system that harvests the grain and the residue at the same time in a single stream, because additional equipment would be needed to separate the grain and the residue, and this mixture of crops may change a producer's eligibility for government programs and crop insurance. Stover is chopped into two-inch pieces and blown into a wagon running alongside the combine. Currently, this attachment system is estimated to cost between $35,000 and $50,000.[23] The system is equipped with a switch to shut off the attachment and allow the residue to be left in a windrow behind the combine should residue harvest interfere with or slow grain harvest. Work continues to ensure that the use of this system does not slow down conventional grain harvest, regardless of the amount of residue the producer chooses to remove.

A one-pass harvesting system allows for residue to be harvested with the grain and keeps the residue from ever touching the ground, which may cause soil contamination and make conversion

[20] S. C. Brechbill and W. E. Tyner, *The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electrical Utility Facilities*, Working Paper 08-03, Department of Agricultural Economics, Purdue University (West Lafayette, IN), April 2008, hereafter referred to as Brechbill and Tyner (2008).
[21] Ibid.
[22] S. R. Schill, "Collecting Mountains of Stover," *Ethanol Producer Magazine*, 2007.
[23] J. Bernick, "One-Pass Stover Harvest," *AgWeb online Farm Journal*, January 10, 2009, at http://www.agweb.com/article/One-Pass_Stover_Harvest_202067/, hereafter referred to as Bernick (2009).

to liquid fuels less efficient. However, a current shortcoming of this method is that residue coming directly from the combine only has a density of about 3 to 4 pounds per cubic foot, while the density would need to be between 12 and 14 pounds per cubic foot to transport it efficiently and fill a truck to its allowed weight limit.[24]

Research is also being conducted to determine at what height residue should be cut. Corn plants tend to have more moisture in the lower part of the plant, making this portion less efficient for conversion as moisture must be removed prior to conversion; this portion also is best left on the field to protect against soil erosion. The upper part and the cobs, however, have lower moisture contents and are most suitable for producing biofuels to make pretreatment and processing as efficient as possible.[25]

While residues are convenient because they accompany the primary crop, there is no reason that they must be removed and no long-term commitment to do so unless the producer enters into a contract with the plant. Perennial grasses, however, are a commitment that must be harvested each year for the life of the stand.

Dedicated Tree Crops

Short-rotation woody crops grown for biomass on agricultural or other open land may include hardwood varieties such as poplar and willow. These trees are commercially grown as a crop and are adaptable to many different regions throughout the country. Short-rotation woody crops are attractive as a biomass feedstock because they re-grow quickly following harvest. Some trees are already being harvested to make pulp and other small wood products. Short-rotation woody crops also provide environmental benefits such as low inputs, improved soil and water quality, reduced CO_2 emissions, and enhanced biodiversity.[26]

To establish short-rotation woody crops, cuttings from year-old trees taken during the dormant season must be planted. In addition to high establishment costs (as with dedicated energy crops), it takes three to four years before the trees are ready to be harvested and begin yielding commercial returns. The life of the entire stand will be at least 20 years, and multiple (but not annual) harvests will take place. For example, seven to eight harvests (i.e., harvests every three to four years) may occur during the life of a willow tree crop.[27] During the growing time, very little annual maintenance is needed. Cost reduction for tree crop production will likely come from increased yields and production efficiency, as well as a mechanism for valuing environmental benefits.[28] Poplar and willow hybrids that will increase yield potential and reduce lignin content are currently being researched. Transportation efficiencies can also be achieved as stands of dedicated tree crops can be grown close to the conversion facilities and do not have to be trucked from commercial forests. Storage is less of an issue with tree crops because they can be stored on the stump and harvested as needed.

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[24] Bernick (2009).

[25] A. Perry, "Cellulosic Ethanol from Corn Stover: Calculating—and Improving—the Bottom Line," *Agricultural Research*, vol. 56, no. 9, October 2008, pp. 14-15.

[26] State University of New York, College of Environmental Science and Forestry, *EcoWIllow*, v. 1.2, undated, at http://www.esf.edu/willow/default.htm, hereafter referred to as State Univ. of New York (undated).

[27] T. A. Volk, T. Verwijst, P. J. Tharakan, L. P. Abrahamson, and E. H. White, "Growing fuel: a sustainability assessment of willow biomass crops," *Frontiers in Ecology and the Environment* 2(8), 2004, pp. 411-418.

[28] For examples, see CRS Report RL34042, *Provisions Supporting Ecosystem Services Markets in U.S. Farm Bill Legislation*, by Renée Johnson.

Forest Residues

Forest residues include naturally grown trees that may be of poor quality or too small to be used commercially, residues left in the forest after commercial logging, residues from clearing rotten trees that could cause forest fires, and residues from processing mills. Currently these residues, which are sustainable and plentiful, are burned, left in the forest to decay, or sent to landfills.[29] Using forest residues can mitigate greenhouse gases, improve the health of forests, and avoid catastrophic fires and diseases. Collecting residues from within a forest, however, can be difficult, because efficient equipment has not been developed and most commercial logging operations are not set up to handle residues. Currently, the more efficient harvesting options chosen by large-scale logging operations are methods that harvest round wood and biomass simultaneously. Similar to one-pass corn and corn stover harvesters, these systems do not require major changes to the current operation and do not add extra steps to the harvest process. However, one-step harvesters are capital-intensive and are best suited for larger tracts of land.[30]

Forest biomass that does not come from a mill will be bulky, dirty, and high in moisture. Residues coming directly from the mill are advantageous, because they have lower moisture content and are in a more consistent form. However, these mill residues, which include bark, chunks of wood, shavings, and sawdust, are currently being used to create energy for processing mills or in other wood products, which may not leave much residue available for biofuel production.

The current language of the Energy Independence and Security Act of 2007 puts restrictions on the types of land from which residues can be collected for use as a cellulosic feedstock. Residues cannot be collected from federal lands, old-growth forests, or imperiled forests. It is uncertain whether the current limited definition would be a barrier to the production of cellulosic biofuels, as feedstocks vary in their distribution and ownership among regions. Woody biomass, for example, tends to be located on private land in the southeastern United States but on federal lands in the western United States.[31] However, H.R. 2454, the American Clean Energy and Security Act passed by the House of Representatives on June 26, 2009, would broaden the definition of renewable biomass to its farm bill definition, which allows renewable biomass to include that which is removed from federal lands.[32] The Senate has yet to consider the bill.

To deal with the bulky nature of forest biomass, it must be condensed by chipping, grinding, or bundling.[33] Chipping is the most efficient and least expensive method, but the knife blades can be damaged by dirt and other foreign material, which sometimes results in a preference for the grinding method. Forest biomass in both of these forms (chipped or ground) can be stored for several weeks but will eventually begin to decay. Bundling is the least efficient and most expensive option; however, bundles can be stored up to nine months with only a 10% loss.[34]

[29] Taylor (2009).

[30] W. Hubbard, L. Biles, C. Mayfield, S. Ashton (eds.), *Sustainable Forestry for Bioenergy and Bio-based Products: Trainers Curriculum Notebook*, Southern Forest Research Partnership, Inc, (Athens, GA), September 2007.

[31] CRS Report R40529, *Biomass: Comparison of Definitions in Legislation Through the 111th Congress*, by Kelsi Bracmort and Ross W. Gorte.

[32] U.S. Congress, House Committee on Energy and Commerce, H.R. 2454, *The American Clean Energy and Security Act of 2009*, 111th Congress, 1st sess., passed by the House on June 26, 2009.

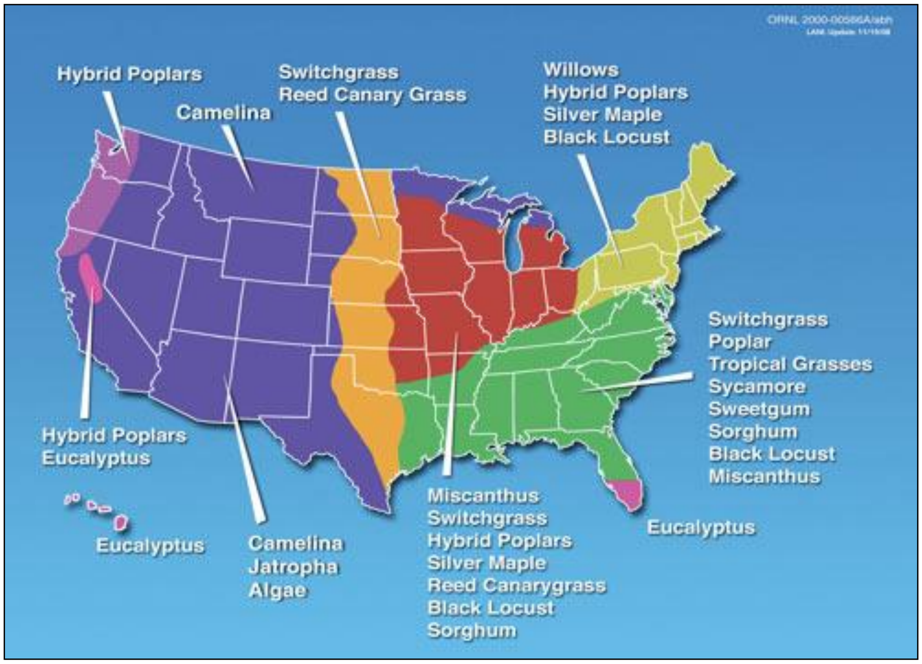
[33] M. H. Pelkki, "Technological Trends and Production Costs for Forestry Biomass," in *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Fdn. Conf. (Little Rock, AR), 2009, hereafter referred to as Pelkki (2009).

[34] Ibid.

Potential Biomass Supply

In making plans to establish commercial-scale cellulosic biofuels plants, knowledge of feedstock supply will be particularly important. However, with no substantial history of biomass crop production and residue collection, supply estimates cannot be based on past experience. Instead, some estimates of supply are based on what is possible and potential. It remains to be seen whether potential supply will accurately translate into actual supply. **Figure 3** shows what types of biomass are expected to come from different geographic regions in the United States. The eastern half of the country boasts the potential for more types of biomass, giving plants that locate there the option of using several types of feedstocks.

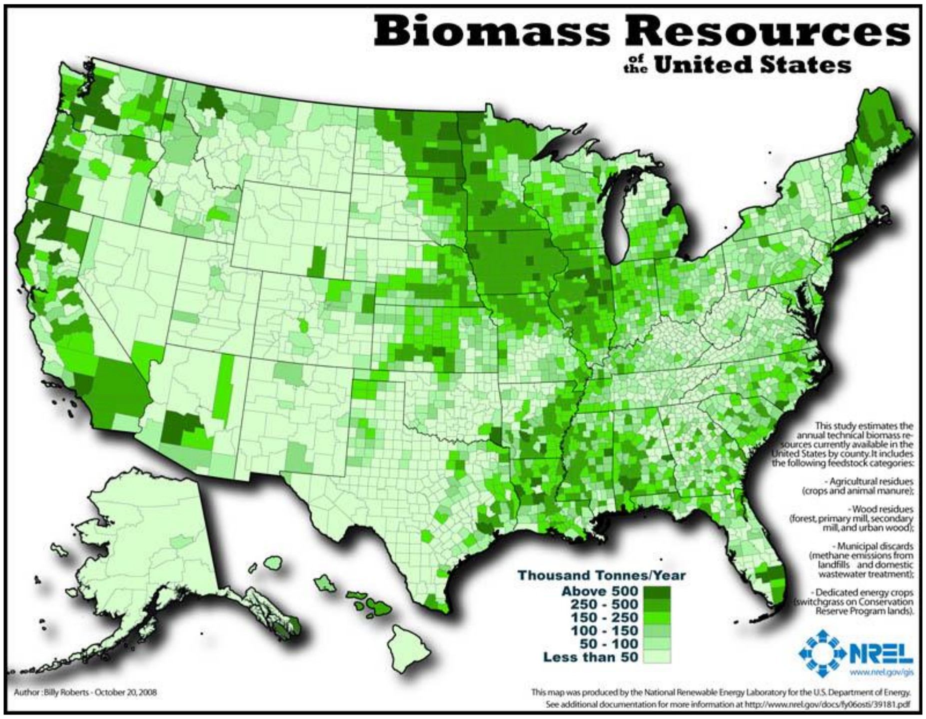
Figure 3. Expected Types of Biomass by Geographic Region in the US



Source: U.S. Department of Energy, "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," *A Research Roadmap Resulting from the Biomass to Biofuels Workshop*, Office of Energy Efficiency and Renewable Energy (Rockville, MD), 2006.

Figure 4 shows the distribution of biomass throughout the United States. Biomass is most densely located in the upper Midwest, Delta, Southeast, and Pacific Coast.

Figure 4. Geographic Distribution of Biomass Resources in the United States



Source: A. Milbrandt, *A Geographic Perspective on the Current Biomass Resource Availability in the United States*, Dept. of Energy, National Renewable Energy Laboratory (Golden, CO), 2005.

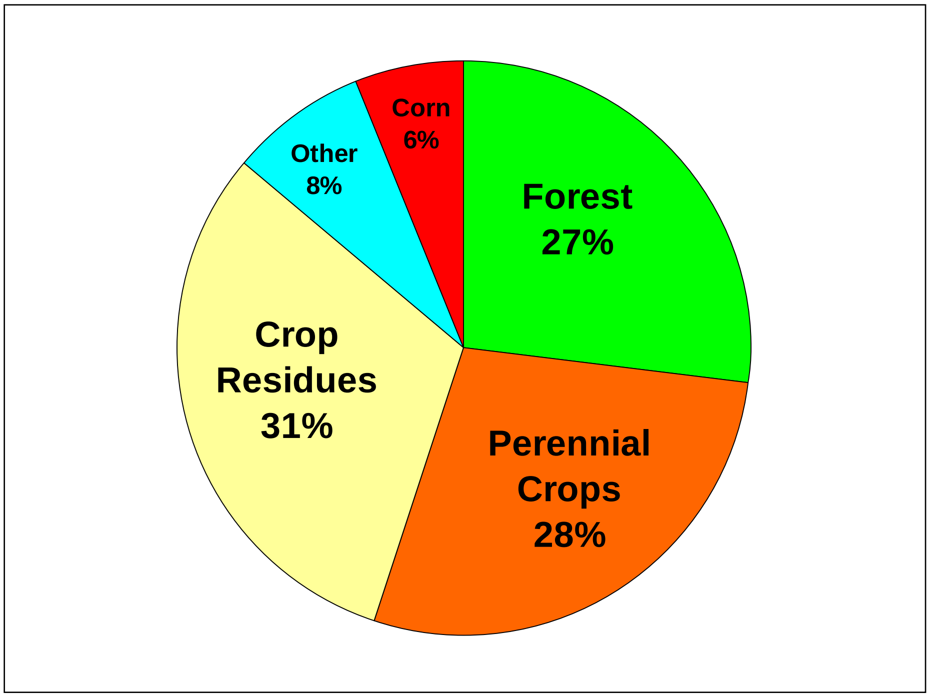
A 2005 study (the so-called "Billion-Ton Study") by the DOE and USDA found that through yield increase and the incorporation of perennial energy crops, forest and agricultural land in the United States could produce over 1.3 billion tons of biomass per year.[35] Of the 1.3 billion ton total in the 2005 study, 428 million dry tons would come from agricultural residues, 377 million dry tons would come from perennial crops, which include grasses and short rotation woody crops, and 368 million dry tons would come from forestlands. Of the 368 million dry tons from forestlands, 63 million dry tons would come from logging residues, 147 million dry tons would come from mill residues, and 59 million dry tons would come from forest health removals. The rest would come from fuel wood harvests and urban wood waste.[36] The study generated considerable concern that its estimations were overly generous and optimistic, particularly as regards the availability of crop and forest residues and urban waste. As a result, the study is being updated, with the update scheduled for release by the end of 2010.

Figure 5 summarizes what portion of biofuels will be produced from each type of feedstock by the time the cellulosic biofuel industry has matured, according to the Billion-Ton Study. Crop residues, perennial grasses, and forest residues are expected to have nearly equal shares and to account for nearly all of biofuels production.

[35] R. D. Perlack, , L. Wright, A. Turnhollow, R. Graham, B. Stokes, D. Erbach, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, Oak Ridge National Laboratory (Oak Ridge, TN), April 2005, hereafter referred to as Perlack et al, *The Billion-Ton Study* (2005).

[36] Pelkki (2009); and Perlack et al, *The Billion-Ton Study* (2005).

Figure 5. Projected U.S. Biofuel Sources



Source: R. D. Perlack, , L. Wright, A. Turnhollow, R. Graham, B. Stokes, D. Erbach, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, Oak Ridge National Laboratory (Oak Ridge, TN), April 2005.

In sharp contrast to the Billion-Ton Study, the National Academy of Sciences found that with 2008 technologies and practices, a total of 416 million tons of biomass feedstocks could be harvested and produced sustainably for biofuel production, while 548 million tons would be available in 2020 due to more efficient use of land and increases in crop yields.[37] Of that 548 million tons, 366 million tons are expected to come from residues, 164 million tons are expected to come from dedicated energy crops, and 18 million tons are expected to come from yield increases in hay production.

The Environmental Protection Agency (EPA) has estimated that by 2022 agricultural residues will account for 5.7 billion gallons of cellulosic ethanol (4.9 billion gallons from corn stover), forestry biomass will account for 0.1 billion gallons, urban waste will account for 2.3 billion gallons, and dedicated energy crops will account for 7.9 billion gallons, for a total of 16 billion gallons.[38] For corn stover, the agency assumes that the ethanol conversion yield will be 92.3 gallons per dry ton, which equates to 53 million dry tons of corn stover being available. If the average harvested yield is 2 tons/acre (perhaps high), then 26.5 million acres of corn (or roughly one-third of total annual harvested corn acres) would be harvested for stover.

[37] National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, Washington, DC, 2009, hereafter referred to as NAS, *Liquid Transportation Fuels from Coal and Biomass* (2009).

[38] U.S. Environmental Protection Agency, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, EPA-420-R-10-006, Assessment and Standards Division, Office of Transportation and Air Quality, Washington, DC, 2010.

A study based on 1997 data found that there were 36.2 million dry tons of logging residues available in the United States.[39] It was projected that this total would increase by 1.6% by 2010 and 5.1% by 2020. Additionally, a 2009 study from Purdue University found that cropland pasture and other idled land could provide up to 92.6 million acres of land on which to grow switchgrass and *Miscanthus* for cellulosic biofuels production.[40] This land could produce 327 million tons of switchgrass and 833 million tons of *Miscanthus*, for a total of 17 billion to 53 billion gallons of potential ethanol production depending on the fraction of available land used.

These studies arrive at very different conclusions regarding the actual amount of available biomass. BP, one of the major biofuel players in the oil industry, intends to use only dedicated crops. BP believes dedicated crops offer greater potential for achieving the scale of production it is seeking.[41] It remains to be seen on what basis plants make their location decisions. These decisions could be driven by feedstock availability, plant construction, or fuel distribution, just to name a few potentially relevant considerations.

While supply estimates may indicate total availability of biomass, participation rates must also be considered, because the presence of biomass does not guarantee that landowners and producers will provide it to cellulosic biofuel plants. Studies have assumed participation rates ranging from 30% to 80%.[42] Participation rates will likely depend on the size of the plant, the price being paid for biomass by the plant, the cost of harvesting and collecting biomass for a producer of a given size, and the terms of contracts with producers. Participation rates may vary across areas. Differences in weather conditions that affect the ease of harvest also will be important.

Feedstock Production Yields

Feedstock yields have some degree of uncertainty as collection technologies and establishment and maintenance regimens develop. Yields will vary by geographic region, soil characteristics, and water availability. For corn stover, a distinction must be made between what is available and what is removable. Available stover will be a function of the corn yield, while removable stover will be a function of available stover and the percentage of stover deemed appropriate for removal. A one-to-one ratio between corn stover and grain is usually assumed, which means there will be approximately 56 pounds of corn stover for every bushel of corn. Based on the grain yield, the available corn stover yield can be calculated. For example, assuming corn stover moisture content of 15%, grain yields of 125, 150, and 175 bushels per acre will result in 2.9, 3.5, and 4.1 dry tons of corn stover available per acre, respectively.[43] Corn stover moisture content can

[39] J. Gan and C. T. Smith, "Availability of logging residues and potential for electricity production and carbon displacement in the USA," *Biomass and Bioenergy*, 30(12), 2006, pp. 1011-1020.

[40] W. E. Tyner, F. Taheripour, and Y. Han, *Preliminary Analysis of Land Use Impacts of Cellulosic Biofuels*, Argonne National Laboratory and the California Energy Commission, 2009.

[41] Personal communication by Prof. Tyner, Purdue University, with Matt Caswell, BP, undated.

[42] Brechbill and Tyner (2008); R. D. Perlack and A. F. Turhollow, *Assessment of Options for the Collection, Handling, and Transport of Corn Stover*, ORNL/TM-2002/44, Oak Ridge National Laboratory (Oak Ridge, TN), 2002, hereafter referred to as Perlack and Turhollow (2002); D. R. Petrolia, "The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota," *Biomass and Bioenergy* 32(7), 2008, p. 603-612, hereafter referred to as Petrolia (2008); and T. M. Schechinger and J. Hettenhaus, *Corn Stover Harvesting: Grower, Custom Operator, and Processor Issues and Answers: Report on Corn Stover Experiences in Iowa and Wisconsin for the 1997-98 and 1998-99 Crop Years*, ORNL/SUB-04-4500008274-01, Oak Ridge National Laboratory (Oak Ridge, TN), 1999, hereafter referred to as Schechinger and Hettenhaus (1999).

[43] D. R. Petrolia, "Economics of Crop Residues: Corn Stover," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009, hereafter referred to as Petrolia (2009).

be estimated as a function of the grain moisture and the number of days after grain maturity.[44] After initial maturity, grain moisture may be around 40% and stover moisture may be as high as 75%. However, 80 days after maturity is reached, grain moisture and stover moisture can both converge to around 10%. Once mature, the stover moisture will decline at a faster rate than the grain moisture. While the one-to-one stover to grain ratio is quite common, grain moisture above 18% may result in 0.8-to-one being a more realistic ratio for calculating the available corn stover yield.[45] Regardless of the stover-to-grain ratio, available corn stover will be a function of corn yield, and removable corn stover will be a function of the removal rate. Both corn yield and the appropriate removal rate will vary from field to field, which makes predicting the removable corn stover yield difficult. Overall, areas where grain yields are high will also have high residue yields, but the amount that is ultimately removed and used will depend on the ability of the producer to harvest or collect residues and how much can be removed while still maintaining the integrity and quality of the soil.

Perennial grasses will have lower yields in the years immediately after establishment and will then increase to peak yield once mature. There is also the chance that seeds may remain dormant and do not grow after planting. This will require the grasses to be planted again, which doubles the establishment costs and delays the first harvest and the eventual peak yield. Perennial grass yields will tend to be higher in regions where temperatures are high and winters are short, in order to provide a longer harvest window and longer growing season.[46]

Forest residue yields are a function of yield from conventional logging. For hardwood stands, 20% to 40% of the initial yield can be recovered as additional residue.[47] As with corn stover, collection technology and the available resources of a given type and size of operation will impact the amount of residue collected.

Table 2 summarizes the estimates of biomass yield from several studies in different geographic regions. A majority of these yields are from research test plots, from small-scale producer experiments, or based on assumptions for the region. As with yields for other crops, biomass yields will not be uniform and constant across a given area. Much variation will depend on weather conditions, soil types, topography, and producer expertise and experience. For corn stover, up to 5 tons per acre could be available but not removable. Switchgrass yields are between 3 and 6 tons per acre, with yields going above that in warmer climates. *Miscanthus* seems to average about 13 tons per acre on the few sites where it has been planted but will increase in warmer climates as well. Short-rotation woody crops yield 2 to 5 tons per acre per year. Forest residue yields are calculated as a percentage of the yield of the forest stand.

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[44] S. Sokhansanj, A. Turhollow, and E. Wilkerson, *Development of the Integrated Biomass Supply Analysis and Logistics Model (IBSAL)*, Oak Ridge National Laboratory (Oak Ridge, TN), 2008, hereafter referred to as Sokhansanj et al. (2008).

[45] L. O. Pordesimo, W. C. Edens, and S. Sokhansanj, "Distribution of above-ground biomass in corn stover," *Biomass and Bioenergy*, 26(4), 2004, pp. 337-343.

[46] F. Epplin, "Alternative Energy and Agriculture: Perspectives on Cellulosic Feedstock and Cellulosic Biorefineries," *Southern Association of Agricultural Sciences* (Altanta, GA), 2009, hereafter referred to as Epplin (2009).

[47] Petrolia (2009).

Table 2. Biomass Yields by Feedstock

Location	Yield	Source (Year)
Corn Stover		
Midwest	3.6 available tons/acre 1.7 removable tons/acre	Sokhansanj and Turhollow (2002)[a]
IN	4.25 available tons/acre 1.6 to 3.0 removable tons/acre (depending on harvesting technique)	Brechbill and Tyner (2008)[b]
Midwest	3.6 available tons/acre 1.5 removable tons/acre	Sokhansanj, Turhollow, and Perlack (2002)[c]
Midwest	2.94 removable tons/acre	Quick (2003)[d]
IA	4 to 5 available tons/acre 1.5 to 3.5 removable tons/acre	Glassner et al. (1998)[e]
IA and WI	1.25 to 1.55 removable tons/acre	Schechinger and Hettenhaus (1999)[f]
IA	3.1 to 4.8 available tons/acre 2.2 to 3.3 removable tons/acre	Atchison and Hettenhaus (2003)[g]
Not location specific	3.3 available tons/acre 1.1 removable tons/acre	Perlack and Turhollow (2002)[h]
IA	4.4 available tons/acre 2.9 removable tons/acre	Sokhansanj et al. (2008)[i]
Switchgrass		
IA	4.0 tons/acre	Duffy (2008)[j]
OK	4.0 tons/acre	Epplin (1997)[k]
OK	3.75 to 6.50 tons/acre	Epplin et al. (2007)[l]
TN	6.45 tons/acre	Garland (2008)[m]
IL	2.4 tons/acre	Khanna (2008)[n]
IL	4.2 tons/acre	Khanna et al. (2008)[o]
ND, SD, NE	3.12 tons/acre	Perrin et al. (2008)[p]
WI	4.0 to 5.8 tons/acre	Vadas et al. (2008)[q]
	6.17 tons/acre (implied)	U.S. EPA (2009)[r]
IA	4.0 tons/acre	Duffy and Nanhou (2001)[s]
AR	5.0 tons/acre	Popp and Hogan (2007)[t]
IN	5.0 tons/acre	Brechbill and Tyner (2008)
MN, ND, SD	2.0 to 4.0 tons/acre	Tiffany et al. (2006)[u]
ND	2.7 to 3.5 tons/acre	Bangsund et al. (2008)[v]
IL	4.6 tons/acre	Heaton et al. (2008)[w]
TN	4.3 to 8.8 tons/acre	Downing and Graham (1996)[x]
Southeast	7 to 16 tons/acre	Comis (2006)[y]
Western Corn Belt	5 to 6 tons/acre	Comis (2006)
ND	1 to 4 tons/acre	Comis (2006)
IA and IL	2.58 tons/acre	Khanna and Dhungana (2007)[z]

Location	Yield	Source (Year)
Miscanthus		
IL	13 to 19 tons/acre	Khanna et al. (2008)
IL	13.2 tons/acre	Heaton et al. (2008)
IL	8.9 tons/acre	Khanna et al. (2008)
Europe	4.5 to 13.4 tons/acre in central and northern Europe, up to 20 tons/acre in southern Europe	Lewandowski et al. (2003)[aa]
Poplar/Willow		
TN	5 tons/acre/year	Mercker (2007)[bb]
TN	2.4 to 4.3 tons/acre/year	Downing and Graham (1996)
MN	2.4 tons/acre/year	Downing (2004)[cc]
MN	3.8 tons/acre/year	Lazarus (2008)[dd]
MN	1.8 to 3.0 tons/acre/year	Updegraff, Baughman, and Taff (2004)[ee]
IN	5 tons/acre/year	NAS (2009)[ff]
NY	5 tons/acre/year	State Univ. of New York (undated)[gg]
Hardwood Residues		
2009	20%-40% of stem wood volume from conventional logging	Pelkki (2009)[hh]

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

a. S. Sokhansanj and A. Turhollow, "Baseline Cost for Corn Stover Collection," *Applied Engineering in Agriculture*, 18(5), 2002, pp. 525-530.

b. S. C. Brechbill and W. E. Tyner, *The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electrical Utility Facilities*, Working Paper 08-03, Department of Agricultural Economics, Purdue University (West Lafayette, IN), April 2008.

c. S. Sokhansanj, A. Turhollow, and R. Perlack, "Stochastic Modeling of Costs of Corn Stover Costs Delivered to an Intermediate Storage Facility," *American Society of Agricultural Engineers Annual International Meeting,* CIGR XVth World Congress (Chicago, IL), 2002.

d. G. R. Quick, "Single-Pass Corn and Stover Harvesters: Development and Performance," *Proceedings of the International Conference on Crop Harvesting and Processing*, ASABE Publication Number 701P1103e, American Society of Agricultural and Biological Engineers (Louisville, KY), 2003.

e. D. A. Glassner, J. R. Hettenhaus, and T. M. Schechinger, "Corn Stover Collection Project," *BioEnergy '98: Expanding BioEnergy Partnerships*, 1998, pp. 1100-1110.

f. T. M. Schechinger and J. Hettenhaus, *Corn Stover Harvesting: Grower, Custom Operator, and Processor Issues and Answers: Report on Corn Stover Experiences in Iowa and Wisconsin for the 1997-98 and 1998-99 Crop Years*, ORNL/SUB-04-4500008274-01, Oak Ridge National Laboratory (Oak Ridge, TN), 1999.

g. J. E. Atchison and J. R. Hettenhaus, *Innovative Methods for Corn Stover Collecting, Handling, Storing and Transporting*, NREL/SR-510-33893, National Renewable Energy Laboratory (Golden, CO), March 2003.

h. R. D. Perlack and A. F. Turhollow, *Assessment of Options for the Collection, Handling, and Transport of Corn Stover*, ORNL/TM-2002/44, Oak Ridge National Laboratory (Oak Ridge, TN), 2002.

i. S. Sokhansanj, A. Turhollow, and E. Wilkerson, *Development of the Integrated Biomass Supply Analysis and Logistics Model (IBSAL)*, Oak Ridge National Laboratory (Oak Ridge, TN), 2008.

j. M. Duffy, *Estimated Costs for Production, Storage, and Transportation of Switchgrass*, A1-22, Iowa State Univ. (ISU) Extension, ISU (Ames, IA), 2008.

k. F. M. Epplin, "Cost to produce and deliver switchgrass biomass to an ethanol-conversion facility in the southern plains of the United States," *Biomass and Bioenergy*, 11(6), 1997, pp. 459-467.

l. F. M. Epplin, C. D. Clark, R. K. Roberts, and S. Hwang, "Challenges to the Development of a Dedicated Energy Crop," *American Jl of Agr. Economics* 85(5), 2007, pp. 1296-1302.

m. C. D. Garland, *Growing and Harvesting Switchgrass for Ethanol Production in Tennessee*, University of Tennessee Biofuels Initiative, Univ. of Tennessee (Knoxville, TN), 2008.

n. M. Khanna, "Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?" *Choices* 23(3), 2008, pp. 16-21.

o. M. Khanna, B. Dhungana, and J. Clifton-Brown, "Cost of Producing Miscanthus and Switchgrass for Bioenergy in Illinois,"S *Biomass and Bioenergy*, 32(6), 2008, pp. 482-493.

p. R. Perrin, K. Vogel, M. Schmer, and R. Mitchell., "Farm-Scale Production Cost of Switchgrass for Biomass," *Bioenergy Research* Vol. 1, No. 1, 2008, pp. 91-97.

q. P. A. Vadas, K. H. Barnett, and D. J. Undersander, "Economics and Energy of Ethanol Production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA," *Bioenergy Research* Vol. 1, No. 1, 2008, pp. 44-55.

r. U.S. EPA, *Draft Regulatory Impact Analysis: Changes to the Renewable Fuel Standard Program*, EPA-420-D-09-001, Office of Transportation and Air Quality, May 2009.

s. M. Duffy and V. Nanhou, *Costs of Producing Switchgrass for Biomass in Southern Iowa*, PM 1866, University Extension, Iowa State University (Ames, IA), April 2001.

t. M. Popp and J. R. Hogan, "Assessment of Two Alternative Switchgrass Harvest Transport Methods," *Biofuels, Food, and Feed Tradeoffs*, Farm Foundation Conference (St. Louis, MO), 2007.

u. D. G. Tiffany, B. Jordan, E. Dietrich, B. Vargo-Daggett, *Energy and Chemicals from Native Grasses: Production, Transportation and Processing Technologies Considered in the Northern Great Plains*, Staff Paper P06-11, University of Minnesota, Department of Applied Economics, College of Food, Agricultural & Natural Resource Sciences, 2006.

v. D. A. Bangsund, E. A. DeVuyst, and F. L. Leistritz, "Evaluation of Breakeven Farm-gate Switchgrass Prices in South Central North Dakota," *Agribusiness and Applied Econ.s Report No. 632-S*, N. Dak. St. Univ. (Fargo, ND), Aug. 2008.

w. E. A. Heaton, , F. G. Dohleman, and S. P. Long, "Meeting US biofuel goals with less land: the potential of Miscanthus," *Global Change Biology* 14(9), Sept. 2008, pp. 2000-2014.

x. M. Downing and R. L. Graham, "The Potential Supply and Cost of Biomass From Energy Crops in the Tennessee Valley Authority Region," *Biomass and Bioenergy* 11(4), 1996, pp. 283-303.

y. D. Comis, "Switching to Switchgrass Makes Sense," *Agricultural Research*, Agricultural Research Service, USDA, 2006.

z. M. Khanna and B. Dhungana, "Economics of alternative feedstocks," Chapter 8, *Corn-based ethanol in Illinois and the US: A Report from Department of Agricultural and Consumer Economics, University of Illinois*, University of Illinois (Urbana-Champaign, IL), 2007, pp. 129-146.

aa. I. Lewandowski, J. Scurlock, E. Lindvall, and M. Christou, "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe," *Biomass and Bioenergy* 25(4), 2003, pp. 335-361.

bb. D. Mercker, *Short Rotation Woody Crops for Biofuel*, SP702-C, University of Tennessee Extension, University of Tennessee Biofuels Initiative, University of Tennessee (Knoxville, TN), 2007.

cc. M. Downing, *Hybrid Poplar Production in Minnesota on a Large Scale*, in *Agriculture as a Producer and Consumer of Energy,* Farm Foundation Conference (Arlington, Virginia), 2004.

dd. W. Lazarus, *Energy Crop Production Costs and Breakeven Prices Under Minnesota Conditions*, Staff Paper P08-11, Department of Applied Economics, Univ. of Minnesota, 2008.

ee. K. Updegraff, M. J. Baughman, and S. J. Taff, "Environmental benefits of cropland conversion to hybrid poplar: economic and policy considerations," *Biomass and Bioenergy* 27(5), 2004, pp. 411-428.

ff. National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, Washington, DC, 2009.

gg. State University of New York, College of Environmental Science and Forestry, *EcoWIllow*, v. 1.2, undated, at http://www.esf.edu/willow/default.htm.

hh. M. H. Pelkki, "Technological Trends and Production Costs for Forestry Biomass," in *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Fdn. Conf. (Little Rock, AR), 2009.

Production Costs

Several studies estimate the production costs of different types of biomass. These cost estimates can vary for a wide variety of reasons. The location and timing of the study can influence the cost of inputs, labor, and equipment. Yields will affect the number of tons over which to spread per-acre costs. Many of the major differences among cost studies relate to assumptions regarding what to exclude and include in the calculations. Explicitly identifying the assumptions and parameters of differing studies can often explain discrepancies. No one set of assumptions and parameters is thought to be universally correct.

Corn stover production costs primarily include collection after corn grain harvest and nutrient replacement. What tends to make corn stover a less expensive biomass feedstock is that it is a byproduct. All establishment costs are accounted for in corn grain production. When left on the ground, corn stover provides protection from soil erosion and serves to retain nutrients while land is fallow. Depending on the amount of stover removed after harvest, additional nutrients will need to be added before planting the following year. Fertilizer costs will increase with energy costs, which will also increase the cost of corn stover. In addition, with increasing corn yields, it may be useful to remove part of the stover to prepare the field for crop operations the next year.

Table 3 breaks down the production costs for corn stover from several studies. The farm gate cost per ton ranges from $12 to $67. Low estimates are often from older studies that assumed lower fertilizer and energy costs. Some studies also did not consider nutrient replacement costs at all, which leads to lower total costs. The total cost in some instances only considers harvest and nutrient replacement, while other studies include a payment to the producer and assume some storage loss.

Table 3. Corn Stover Production Costs

Source (Year)	Location	Harvest ($/ton)	Fertility Replacement ($/ton)	Payment to Land Owner or Farmer ($/ton)	Harvestable Yield (tons/acre)	Farm Gate Cost ($/ton)
Gallagher et al. (2003)[a]	KS	$5.96	$6.47	N/A	3.33	$12
Gallagher et al. (2003)	IA	$6.27	$6.46	N/A	3.13	$13
Glassner et al. (1998)[b]	IA	$14.60	N/A	$3-$15	1.5-3.0	$18-30
Sokhansanj and Turhollow (2002)[c]	Midwest	$20-$22	N/A	N/A	1.7	$20-$22
Sokhansanj et al. (2008)[d]	IA	$21.95	N/A	N/A	2.9	$24
Graham et al. (2007)[e]	US	$18-$33	$6.50	N/A	1.4-2.3	$25-$40
Brechbill and Tyner (2008)[f]	IN	$5.88	$15.64	15% of per ton cost	1.6-3.0	$35
Perlack and Turhollow (2002)[g]	Not location-specific	$22.30	Covered by payment to farmer	$10	1.1	$35-$37
U.S. EPA (2009)[h]	IN	$23.73	$11.81	$10	2.0	$43-$46

Source (Year)	Location	Harvest ($/ton)	Fertility Replacement ($/ton)	Payment to Land Owner or Farmer ($/ton)	Harvestable Yield (tons/acre)	Farm Gate Cost ($/ton)
Petrolia (2008)[i] and Eidman et al. (2009)[j]	MN	$20	$4.21 for 2000-2004 prices $10.64 for 2007 prices	$20	1.25-1.55	$53-$56
Aden et al. (2002)[k]	IA	$26	$7	$10	2.2	$56
Khanna (2008)[l]	IL	$35.05	$8.27	$24	1.85	$67

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

a. P. Gallagher, M. Dikeman, J. Fritz, E. Wailes, W. Gauther, and H. Shapouri, *Biomass from Crop Residues: Cost and Supply Estimates*, Agricultural Economic Report No. 819, U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, February 2003.

b. D. A. Glassner, J. R. Hettenhaus, and T. M. Schechinger, "Corn Stover Collection Project," *BioEnergy '98: Expanding BioEnergy Partnerships*, 1998, pp. 1100-1110.

c. S. Sokhansanj and A. Turhollow, "Baseline Cost for Corn Stover Collection," *Applied Engineering in Agriculture*, 18(5), 2002, pp. 525-530.

d. S. Sokhansanj, A. Turhollow, and E. Wilkerson, *Development of the Integrated Biomass Supply Analysis and Logistics Model (IBSAL)*, Oak Ridge National Laboratory (Oak Ridge, TN), 2008.

e. R. L. Graham, R. Nelson, J. Sheehan, R. D. Perlack, and L. L. Wright., "Current and Potential US Corn Stover Supplies," *Agronomy Journal* 99(1), 2007, pp. 1-11.

f. S. C. Brechbill and W. E. Tyner, *The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electrical Utility Facilities*, Working Paper 08-03, Department of Agricultural Economics, Purdue University (West Lafayette, IN), April 2008.

g. R. D. Perlack and A. F. Turhollow, *Assessment of Options for the Collection, Handling, and Transport of Corn Stover*, ORNL/TM-2002/44, Oak Ridge National Laboratory (Oak Ridge, TN), 2002.

h. U.S. EPA, *Draft Regulatory Impact Analysis: Changes to the Renewable Fuel Standard Program*, EPA-420-D-09-001, Office of Transportation and Air Quality, May 2009.

i. D. R. Petrolia, "The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota," *Biomass and Bioenergy* 32(7), 2008, p. 603-612.

j. V. Eidman, D. Petrolia, H. Huang, and S. Ramaswamy. *The Economic Feasibility of Producing Ethanol from Corn Stover and Hardwood in Minnesota*, Staff Paper P09-3, Department of Applied Economics, University of Minnesota, 2009.

k. A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas, *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*, NREL/TP-510-32438, National Renewable Energy Laboratory (Golden, CO), U.S. Department of Energy, June 2002.

l. M. Khanna, "Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?" *Choices* 23(3), 2008, pp. 16-21.

Table 4 outlines the method and some assumptions used in two recent corn stover cost estimate studies that arrive at very different estimates for the per-ton cost of corn stover. A few differences to note include yield, nutrient replacement, storage, densification, and payment to the producer.

- Because the Brechbill and Tyner study allows for higher removal rates, the yield is higher, which helps decrease per-ton costs.
- The Eidman and Petrolia studies do not include nitrogen costs in nutrient replacement, because they assume a corn-soybean rotation.
- The Brechbill and Tyner study assumes bales of stover will be stored along the edge of the field until needed by the plant, while the Eidman and Petrolia studies

assume that bales are transported to a regional storage facility and sometimes even stored under roof. The additional transportation and the construction of a storage facility serve to increase per-ton costs.

- The Eidman and Petrolia studies also allow for the possibility of densification just before the stover is transported to the plant. This serves to increase the density of the stover and reduce transportation costs by allowing more to be loaded onto each truck. The Brechbill and Tyner study did not consider this and assumed that stover would be hauled to the plant in bale form.
- Finally, Brechbill and Tyner provide a payment to the producer that is 15% of the cost of production. In the case of corn stover, this is approximately $5 per dry ton. The Eidman and Petrolia studies pay $20 per dry ton.

Table 4. Assumptions and Parameters Used in Two Corn Stover Cost Studies

	Sources	
Item	**Brechbill and Tyner (2008)[a]**	**Petrolia (2008),[b] Petrolia (2009),[c] and Eidman et al. (2009)[d]**
Location	Indiana	Minnesota, Iowa, South Dakota
Yield	4.25 available tons per acre with 1.6 to 3.0 removable tons per acre	One-to-one stover to grain ratio, grain yields vary depending on the specific site, approximately 1.3 to 1.6 removable tons per acre
Nutrient replacement	Replace nitrogen, phosphorus, and potassium at a cost of $15.64 per ton of stover removed	Replace phosphorus and potassium at a cost of $4.21 per ton of stover removed based on 2000 to 2004 average fertilizer prices and $10.64 per ton of stover removed based on 2007 fertilizer prices
Participation rate	50% and 75%	50%
Harvest method	Baling only, raking and baling, or shredding, raking, and baling	Baling only and shredding, raking, and baling
Equipment	Owned equipment for farm sizes of 500, 1,000, 1,500, and 2,000 acres or custom hired operators	Purchased shredder, rake, baler, bale picker, and telehandler
Removal rate	38% for baling only, 52.5% for raking and baling, and 70% for shredding, raking, and baling	30% when using round bales, 40% when using square bales
Baling	1,000 pound round bales wrapped in either twine, net wrap, or plastic wrap	880 pound round bales wrapped in plastic mesh and 1,598 pound rectangular bales wrapped in twine
Storage	Bales stored at the edge of the field until needed by the plant, storage premium paid after six months of storage	Round bales stored outdoors since wrapped with plastic, rectangular bales stored indoors
Dry matter loss	Depends on method used to bale the stover, 3.13% per month of storage when using twine, 1.4% per month of storage when using net wrap, 1.025% per month of storage when using plastic wrap	2% storage loss for both types of bales

<table>
<tr><th rowspan="2">Item</th><th colspan="2">Sources</th></tr>
<tr><th>Brechbill and Tyner (2008)[a]</th><th>Petrolia (2008),[b] Petrolia (2009),[c] and Eidman et al. (2009)[d]</th></tr>
<tr><td>Densification</td><td>Not applicable</td><td>Densification facility is located next to the central storage facility and densification would take place immediately before stover is taken to the plant. Results in significant cost reduction in transportation of round bales and only slight cost reduction in transportation of rectangular bales.</td></tr>
<tr><td>Transportation</td><td>Flatbed semi-trucks, owned equipment for farm sizes of 500, 1,000, 1,500, and 2,000 acres or custom hired operators, bales transported directly from the edge of the field to the plant when requested by the plant</td><td>Bales transported via flatbed semi-truck from the edge of the field to a central storage facility</td></tr>
<tr><td>Payment to producer</td><td>15% of the per ton product cost</td><td>$20 per dry ton</td></tr>
<tr><td>Farm gate cost (not including transport)</td><td>$35 per dry ton</td><td>Approximately $53 per dry ton for rectangular bales, $56 per dry ton for round bales, and $76 per dry ton when densified</td></tr>
<tr><td>Transportation</td><td>13 dry tons per loaded trailer
$2.60 per loaded mile
$0.20 per mile per dry ton
For a 13 dry ton load travelling 25 miles, $5.00 per dry ton in total transportation cost</td><td>22.4 dry tons per loaded trailer with rectangular bales
11.9 dry tons per loaded trailer with round bales
23 dry tons per loaded trailer with densification
$2.82 per loaded mile for 0 to 25 miles
$2.22 per loaded mile for 26 to 100 miles
$1.96 per loaded mile for over 100 miles
For rectangular bales travelling 25 miles, $3.15 per dry tons in total transportation cost
For round bales travelling 25 miles, $5.92 per dry tons in total transportation cost
For densified bales travelling 25 miles, $3.07 per dry tons in total transp. cost</td></tr>
<tr><td>Total delivered cost
(25 miles)</td><td>$40 per dry ton</td><td>$56.15 per dry ton (rectangular bales)
$61.92 per dry ton (round bales)
$79.07 per dry ton (densified)</td></tr>
</table>

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

a. S. C. Brechbill and W. E. Tyner, *The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electrical Utility Facilities*, Working Paper 08-03, Department of Agricultural Economics, Purdue University (West Lafayette, IN), April 2008.

b. D. R. Petrolia, "The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota," *Biomass and Bioenergy* 32(7), 2008, p. 603-612.

c. D. R. Petrolia, "Economics of Crop Residues: Corn Stover," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009.

d. V. Eidman, D. Petrolia, H. Huang, and S. Ramaswamy. *The Economic Feasibility of Producing Ethanol from Corn Stover and Hardwood in Minnesota*, Staff Paper P09-3, Department of Applied Economics, University of Minnesota, 2009.

Even without seeing the exact calculations involved in each of these studies, breaking down the assumptions of the studies can help determine the source of differences in total costs. This same exercise can be done with switchgrass studies, and differences in land rent, establishment, maintenance, harvest, and storage can account for major total cost differences.

Perennial grasses production costs are comprised of both one-time establishment and annual maintenance costs. Yields for these grasses may take up to three years to reach their peak, which results in high costs and low benefits initially. Growing perennial grasses is also a relatively long-term commitment of resources. Deciding to plant perennial grasses means harvesting each year for the life of the stand.

Table 5 breaks down the production costs for switchgrass from several studies. The farm gate cost per ton ranges from $23 to $114. A major factor in the difference among the estimates is the assumed yield, which for the studies mentioned below ranges from 2.4 to 8.8 tons per acre. Another factor accounting for differences in switchgrass production costs is assumptions made regarding land rent. Some studies assume that no land rent is included, some include rent for pastureland or marginal cropland, and others include rent for cropland that might also be used to grow corn or soybeans.

Table 5. Switchgrass Production Costs

Source (Year)	Location	Land Cost ($/acre)	Harvest Method	Harvestable Yield (tons/acre)	Farm-Gate Cost ($/ton)
Epplin (1997)[a]	OK	$30	Large round bales	4.0	$23
Downing and Graham (1996)[b]	TN	Various	Not specified	4.3-8.8	$28 to $64
Epplin et al. (2007)[c]	OK	$60	Large rectangular bales	3.75-6.5	$37-$53
Perrin et al. (2008)[d]	ND, SD, NE	Various	Large round bales	3.12	$42-$71
Bangsund et al. (2008)[e]	ND	$0	Not specified	2.7-3.5	$47 to $76
Khanna et al. (2008)[f]	IL	$0	Large rectangular bales	4.2	$52
Mooney et al. (2008)[g]	TN	$100	Large round bales	8.83	$53
Brechbill and Tyner (2008)[h]	IL	$70	Large round bales	5.0	$55
Garland (2008)[i]	TN	$0	Large round bales	6.45	$62
Ferland (2001)[j]	GA	$20	Not specified	6.0	$66
Carpenter and Mees (2008)[k]	MO	$33	Not specified	4.5	$86
Khanna (2008)[l] based on calculations by Epplin (2009)[m]	IL	$77	Not specified	2.4	$113 (includes foregone profits from a corn and soybean rotation)

Source (Year)	Location	Land Cost ($/acre)	Harvest Method	Harvestable Yield (tons/acre)	Farm-Gate Cost ($/ton)
Duffy (2008)[n]	IA	$80	Large square bales	4.0	$114 (includes transportation to storage, storage in a building, and transportation to the plant)

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

a. F. M. Epplin, "Cost to produce and deliver switchgrass biomass to an ethanol-conversion facility in the southern plains of the United States," *Biomass and Bioenergy*, 11(6), 1997, pp. 459-467.

b. M. Downing and R. L. Graham, "The Potential Supply and Cost of Biomass From Energy Crops in the Tennessee Valley Authority Region," *Biomass and Bioenergy* 11(4), 1996, pp. 283-303.

c. F. M. Epplin, C. D. Clark, R. K. Roberts, and S. Hwang, "Challenges to the Development of a Dedicated Energy Crop," *American Jl of Agr. Economics* 85(5), 2007, pp. 1296-1302.

d. R. Perrin, K. Vogel, M. Schmer, and R. Mitchell., "Farm-Scale Production Cost of Switchgrass for Biomass," *Bioenergy Research* Vol. 1, No. 1, 2008, pp. 91-97.

e. D. A. Bangsund, E. A. DeVuyst, and F. L. Leistritz, "Evaluation of Breakeven Farm-gate Switchgrass Prices in South Central North Dakota," *Agribusiness and Applied Econ.s Report No. 632-S*, N. Dak. St. Univ. (Fargo, ND), Aug. 2008.

f. M. Khanna, B. Dhungana, and J. Clifton-Brown, "Cost of Producing Miscanthus and Switchgrass for Bioenergy in Illinois," *Biomass and Bioenergy*, 32(6), 2008, pp. 482-493.

g. D. F. Mooney et al., "Switchgrass Production in Marginal Environments: A Comparative Economic Analysis across Four West Tennessee Landscapes," selected paper, *American Agricultural Economics Association Annual Meeting*, Orlando, FL, 2008.

h. S. C. Brechbill and W. E. Tyner, *The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electrical Utility Facilities*, Working Paper 08-03, Department of Agricultural Economics, Purdue University (West Lafayette, IN), April 2008.

i. C. D. Garland, *Growing and Harvesting Switchgrass for Ethanol Production in Tennessee*, University of Tennessee Biofuels Initiative, Univ. of Tennessee (Knoxville, TN), 2008.

j. C. Ferland, "Switchgrass for Co-generation Fuel Feasibility," University of Georgia, Center for Agribusiness and Economic Development, Dept. of Agricultural and Applied Economics, University of Georgia (Athens, GA), 2001.

k. B. Carpenter and M. Mees, "Bale, Silage, and Bio-energy, Projected Budgets for 2009," *Agricultural Electronic Bulletin Board*, University of Missouri Extension, 2008.

l. M. Khanna, "Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?" *Choices* 23(3), 2008, pp. 16-21.

m. F. Epplin, "Alternative Energy and Agriculture: Perspectives on Cellulosic Feedstock and Cellulosic Biorefineries," *Southern Association of Agricultural Sciences* (Altanta, GA), 2009.

n. M. Duffy, *Estimated Costs for Production, Storage, and Transportation of Switchgrass*, A1-22, Iowa State Univ. (ISU) Extension, ISU (Ames, IA), 2008.

Table 6 lists production cost estimates for *Miscanthus* from a study conducted at the University of Illinois, the primary location in the United States where *Miscanthus* research is being conducted. Presently, there is not a significant amount of production cost estimates for *Miscanthus*, but many of the same points hold as with switchgrass. This study finds that *Miscanthus* will cost $38 per ton, which is closer to estimates for corn stover than for switchgrass. The major difference relative to switchgrass is the substantially higher yields, which lead to a lower per-ton cost for *Miscanthus*.

Table 6. Miscanthus Production Costs

Source (Year)	Location	Land Cost ($/acre)	Harvest Method	Harvestable Yield (tons/acre)	Farm-Gate Cost ($/ton)
Khanna et al. (2008)[a]	IL	$0	Large rectangular bales	13-19	$38

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed source.

a. M. Khanna, B. Dhungana, and J. Clifton-Brown, "Cost of Producing Miscanthus and Switchgrass for Bioenergy in Illinois," *Biomass and Bioenergy*, 32(6), 2008, pp. 482-493.

Short-rotation woody crops are similar to perennial grasses in the way they are produced. A majority of the cost is incurred in site preparation, in establishment, and in those years when harvest takes place. Harvest, however, does not take place annually.

Table 7 summarizes the production costs for short-rotation woody crops. Total costs will depend on what yield is achieved and the type of land on which trees are established.

Table 7. Short-Rotation Woody Crop Production Costs

Source (Year)	Location	Land Cost ($/acre)	Harvest Method	Harvestable Yield (tons/acre/yr)	Farm-Gate Cost ($/ton)
Downing and Graham (1996)[a]	TN	Various	$17	2.4 to 4.3	$29-$46 on former cropland, $44-$63 on former pasture
State Univ. of New York (2008)	NY	$35	$15.10	5	$52 for 13 yr rotation, $47 for 22 yr rotation
Han (2009)	IN	$90	$15.05	5	$57
Lazarus (2008)[b]	MN	$40	Not specified	3.8	$63

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

a. M. Downing and R. L. Graham, "The Potential Supply and Cost of Biomass From Energy Crops in the Tennessee Valley Authority Region," *Biomass and Bioenergy* 11(4), 1996, pp. 283-303.

b. W. Lazarus, *Energy Crop Production Costs and Breakeven Prices Under Minnesota Conditions*, Staff Paper P08-11, Department of Applied Economics, Univ. of Minnesota, 2008.

Table 8 outlines costs associated with processing forest residues that come directly from the forest. This only includes harvesting to make the forest residues more uniform and does not include transportation costs.

Table 8. Forest Residue Production Rates and Costs

Technology	Production Rates	Cost per Green Ton	Approximate Cost per Dry Ton
Chipping	300-400 tons/day	$8-$12	$11.60-$17.40
Grinding	250-325 tons/day	$10-$12	$14.50-$17.40
Bundling/Baling	100-200 tons/day	$12-$20	$17.40-$29.00

Source: M. H. Pelkki, "Technological Trends and Production Costs for Forestry Biomass," in *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Fdn. Conf. (Little Rock, AR), 2009.

Notes: These costs are cited in terms of green tons. A dry ton will have a moisture content of less than 10%, while a green ton will have a moisture content of 40% to 50% just after harvest. Dry ton costs shown above assume 45% moisture content.

Capital investments for systems to harvest and process forest residues are estimated to cost between $800,000 and $1,200,000.[48] Another study from Minnesota found the delivered cost of hardwood residue to be $40.37 per dry ton plus the cost of transportation.[49]

Two Alternate Cost Studies From 2009

The Idaho National Laboratory and the National Academy of Sciences released studies in 2009 that provide a different perspective and a more comprehensive assessment of feedstock costs. This section summarizes and assesses these studies.

Idaho National Laboratory Monte Carlo Simulation Results

The Idaho National Laboratory[50] looks at three feedstock supply systems; one system produces a non-uniform feedstock[51] and the other two systems produce uniform feedstocks.[52] In order to compare to the other cost estimates already cited, **Table 9** outlines the estimates for the major components of a conventional production process with a non-uniform feedstock for both corn stover and switchgrass. This production technology is meant to represent technology that is available today and suggests that switchgrass costs about $50 per dry ton compared with about $55 per dry ton for corn stover.

Table 9. Conventional Non-Uniform Feedstock Production Costs ($/dry ton)

Biomass Type	Harvest and Collection	Storage	Handling and Transport	Receiving and Preprocessing	Average Total Cost
Corn Stover	$21.61 ± $2.69	$8.11 ± $0.66	$11.93 ± $1.25	$13.74 ± $1.31	$55.39
Switchgrass	$14.92 ± $1.45	$7.08 ± $0.52	$14.13 ± $1.43	$13.47 ± $1.30	$49.60

Source: J. R. Hess, C. T. Wright, K. L. Kenney, and E. M. Searcy, *Uniform-Format Bioenergy Feedstock Supply System Design Report Series: Commodity-Scale Production Of An Infrastructure-Compatible Bulk Solid From Herbaceous Lignocellulosic Biomass*, "Volume A: 'Uniform-Format' Vision and Conventional-Bale Supply System," Table-2.2, NL/EXT-09-17527DRAFT, Idaho National Laboratory (Idaho Falls, ID), April 2009.

Note: Data presented as (Mean Value) +/- (Standard Deviation) were derived from Monte Carlo simulation of a stochastic model. The average cost for a biomass type is the sum of mean values across the four categories.

[48] Pelkki (2009).

[49] V. Eidman, D. Petrolia, H. Huang, and S. Ramaswamy. *The Economic Feasibility of Producing Ethanol from Corn Stover and Hardwood in Minnesota*, Staff Paper P09-3, Department of Applied Economics, University of Minnesota, 2009, hereafter referred to as Eidman et al. (2009).

[50] *Bioenergy Program*, U.S. Department of Energy, Idaho National Laboratory (INL; Idaho Falls, ID), at https://inlportal.inl.gov/portal/server.pt/community/bioenergy/421/bioenergy_main_page.

[51] J. R. Hess, K. L. Kenney, C. T. Wright, R. Perlack, and A. Turhollow, *Corn Stover Availability for Biomass Conversion: Situation Analysis*, INL/JOU-09-15666, Idaho National Laboratory (Idaho Falls, ID), 2009.

[52] J. R. Hess, C. T. Wright, K. L. Kenney, and E. M. Searcy, *Uniform-Format Bioenergy Feedstock Supply System Design Report Series: Commodity-Scale Production Of An Infrastructure-Compatible Bulk Solid From Herbaceous Lignocellulosic Biomass*, "Volume A: 'Uniform-Format' Vision and Conventional-Bale Supply System," Table-2.2, NL/EXT-09-17527DRAFT, Idaho National Laboratory (Idaho Falls, ID), April 2009, p. 26; hereafter referred to as Hess et al. (2009).

National Academy of Sciences Feedstock Costs

The National Academy of Sciences report[53] has estimated biofuel feedstock costs based to some degree on parameters used in the literature and to some degree on expectations about demand for biomass in a mature industry. These estimates are intended to represent the willingness-to-accept price for the last delivered dry ton of biomass and are assumed to be equivalent to the marginal cost of production for the last ton. With an upward sloping marginal cost curve, each additional ton of biomass costs more than the previous ton due to increasing transportation costs. A plant will likely contract its supply and cover the transportation costs, and each producer will receive the farm-gate price, regardless of their distance from the plant. It is assumed that these prices will apply to a mature industry that demands 500 million tons of biomass per year. Assuming a yield of 70 gallons per ton, this will equate to a 35 billion gallon cellulosic biofuel industry. This suggests that plants will have larger capacities and demand biomass from much further distances than currently planned plants or those that will first emerge on a commercial scale.

The National Academy of Sciences panel expects that feedstock costs will decline over time with improvements in crop yields, land management, and logistics, such as handling, storage, and transportation. Cost estimates were done for corn stover, switchgrass, *Miscanthus,* prairie grasses, woody biomass, and wheat straw. Overall, the total feedstock costs determined by the National Academy of Sciences study are higher than most of those predicted in the literature. The following discussion attempts to break down these costs to determine how they were calculated and what portions of the total costs are particularly higher than expected.

Estimates for corn stover, switchgrass, *Miscanthus*, and woody biomass are presented in the following four tables (**Table 10**, **Table 11**, **Table 12**, and **Table 13**). Where applicable, cost estimates include establishment and seeding, nutrient replacement, harvesting and maintenance, storage, chipping, transportation, stumpage fees, and land and opportunity costs.

The results are presented for six estimated ranges: an estimate based on the current literature followed by a low, 50% low (i.e., average of "low" and "baseline"), baseline, 50% high (i.e., average of "high" and "baseline"), and high estimates. The baseline estimate is treated as the midpoint of the range of estimates, whereas the low and high cost scenarios are considered the best case and worse case scenarios, respectively. The 50% low and 50% high estimates are thought to be a more reasonable range. Baseline estimates are considered to be cost estimates for 2008, while the 50% low estimates are considered to apply to 2020.

[53] NAS, *Liquid Transportation Fuels from Coal and Biomass* (2009).

Table 10. Willingness-to-Accept Corn Stover Price per Ton

	Literature Estimate	Low	50% Low	Baseline	50% High	High
Yield	2 to 3 tons/acre	2.5 tons/acre	2.25 tons/acre	2 tons/acre	1.75 tons/acre	1.5 tons/acre
Nutrient Replacement	$4 to $21/ton	$10/ton	$12.50/ton	$15/ton	$17.50/ton	$20/ton
Harvesting and Maintenance	Up to $35/ton	$40/ton	$42.50/ton	$45/ton	$47.50/ton	$50/ton
Storage	$2 to $17/ton	$10/ton	$12.50/ton	$15/ton	$17.50/ton	$20/ton
Transportation	$0.09 to $0.63/tn/mi or 22 to 67 miles	$0.25/tn/mi for 20 miles = $5/ton	$0.30/tn/mi for 25 miles= $7.50/ton	$0.35/tn/mi for 30 miles=$0.50/ton	$0.40/tn/mi for 35 miles= $14/ton	$0.45/tn/mi for 40 miles= $18/ton
Cropland Rental Rates	$0 to $143 per acre	$0/ac = $0/ton	$25/ac = $11/ton	$50/ac = $25/ton	$75/ac = $43/ton	$100/ac = $67/ton
Total Cost ($/ton)		**$65**	**$86**	**$110**	**$140**	**$175**

Source: National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, chapter 2, "Biomass Resources for Liquid Transportation Fuels," Washington, DC, 2009.

Table 11. Willingness-to-Accept Switchgrass Price per Ton

	Literature Estimate	Low	50% Low	Baseline	50% High	High
Yield	0.89 to 9.8 ton/acre	6 ton/acre	5 ton/acre	4 ton/acre	3 ton/acre	2 ton/acre
Establishment and Seeding	$30 to $200/acre converted to $/ton	$75/acre = $12.50/ton	$87.50/ac = $17.50/ton	$100/ac = $25/ton	$112.50/ac = $37.50/ton	$125/ac = $62.50/ton
Nutrient Replacement	$4 to $21/ton	$5/ton	$7.50/ton	$10/ton	$12.50/ton	$15/ton
Harvesting and Maintenance	na	$35/ton	$37.50/ton	$40/ton	$42.50/ton	$45/ton
Storage	$2 to $17/ton	$10/ton	$12.50/ton	$15/ton	$17.50/ton	$20/ton
Transportation	$0.09 to $0.63/ tn/mi for 22 to 67 miles	$0.25/tn/mi for 20 miles = $5/ton	$0.30/tn/mi for 25 miles=$7.50/ton	$0.35/tn/mi for 30 miles=$10.50/ton	$0.40/tn/mi for 35 miles=$14/ton	$0.45/tn/mi for 40 miles=$18/ton
Cropland Rental Rates	$76 to $230/acre	$150/ac = $25/ton	$175/ac = $35/ton	$200/ac = $50/ton	$225/ac =$75/ton	$250/ac = $125/tn
Total Cost ($/ton)		**$93**	**$118**	**$151**	**$199**	**$286**

Source: National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, chapter 2, "Biomass Resources for Liquid Transportation Fuels," Washington, DC, 2009.

Notes: na = not available.

Table 12. Willingness-to-Accept Miscanthus Price per Ton

	Literature Estimate	Low	50% Low	Baseline	50% High	High
Yield (tons/ acre)	3.4 to 17.8 tons per ac	12 ton/acre	10.5 ton/acre	9 ton/acre	7.5 ton/acre	6 ton/acre
Establishment and Seeding	$43 to $350 per ac	$175/ac=$14.58/ton	$200/ac= $19.05/ton	$225/ac = $25/ton	$250/ac=$33.33/ton	$275/ac=$45.83/ton
Nutrient Replacement	$4 to $21/ton	$5/ton	$7.50/ton	$10/ton	$12.50/ton	$15/ton
Harvesting and Maintenance	na	$35/ton	$37.50/ton	$40/ton	$42.50/ton	$45/ton
Storage	$2 to $17/ton	$10/ton	$12.50/ton	$15/ton	$17.50/ton	$20/ton
Transportation	$0.09 to $0.63/ton/mile for 22 to 67 miles	$0.25/ton/mile for 20 miles = $5/ton	$0.30/ton/mile for 25 miles = $7.50/ton	$0.35/ton/mile for 30 miles=$10.50/ton	$0.40/ton/mile for 35 miles = $14/ton	$0.45/ton/mile for 40 miles = $18/ton
Cropland Rental Rates	$76 to $230 per acre	$150/ac= $25/ton	$175/ac = $35/ton	$200/ac = $50/ton	$225/ac = $75/ton	$250/ac =$125/ton
Total Cost ($/ton)		**$82**	**$101**	**$123**	**$150**	**$186**

Source: National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, chapter 2, "Biomass Resources for Liquid Transportation Fuels," Washington, DC, 2009.

Table 13. Willingness-to-Accept Woody Biomass Price per Ton

	Literature Estimate	Low	50% Low	Baseline	50% High	High
Harvesting and Maintenance	na	$35/ton	$37.50/ton	$40/ton	$42.50/ton	$45/ton
Storage	$2 to $17/ton	$0/ton	$5/ton	$10/ton	$15/ton	$20/ton
Chipping	na	$8/ton	$9/ton	$10/ton	$11/ton	$12/ton
Transportation	$0.09 to $0.63 /ton/mile for 22 to 67 miles	$0.40/ton/ mile for 40 miles= $16/ton	$0.45/ton/mile for 45 miles=$20.25/ton	$0.50/ton/ mile for 50 miles= $25/ton	$0.55/ton/ mile for 60 miles= $33/ton	$0.60/ton/ mile for 70 miles= $42/ton
Stumpage	na	$0/ton	$0/ton	$0/ton	$2.50/ton	$5/ton
Total Cost ($/ton)		**$59**	**$72**	**$85**	**$104**	**$124**

Source: National Academy of Engineering, National Academy of Sciences, and National Research Council, "America's Energy Future" Panel on Alternative Liquid Transportation Fuels, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*, chapter 2, "Biomass Resources for Liquid Transportation Fuels," Washington, DC, 2009.

Notes: na = not available.

Corn stover costs (**Table 10**) can be compared to those in **Table 3**. The highest nutrient replacement value found in the literature was around $15 per ton, but it is the baseline value in the National Academy study. The highest harvest cost found in the literature was around $35 per ton, but this is below the low cost value in this study. Compared to harvest and maintenance costs for switchgrass and *Miscanthus*, corn stover costs are assumed to be slightly higher due to requiring additional labor at the same time as grain harvest, which is likely an overstatement since most stover would be harvested after grain. In addition, land rent is included for corn stover as the opportunity cost of land, but since corn stover is a byproduct of corn, the land rent should not be applied to corn stover.

Switchgrass (**Table 11**) and *Miscanthus* (**Table 12**) costs can be compared to those in **Table 5** and **Table 6**, respectively. The land rent/opportunity cost is assumed to be between $150 and $250 per acre. While some perennial grasses may be planted on land that might also be used for corn or soybeans, it is expected that most grasses will initially be planted on more marginal land or pasture land, which likely would have substantially lower land rents. As a result, these land rent costs seem unreasonably high. Storage costs are mostly within the range estimated in the literature. Transportation distances may be slightly higher since assumptions regarding demand are for a mature industry.

Supply Logistics

Low Energy Density Concerns

Some biomass feedstocks, such as agricultural residues and perennial grass feedstocks, have relatively low energy density, which can make transportation more costly, because a limited number of bales can be made to fit on a load. Because trucks become physically full when hauling biomass before reaching their weight limits, more truckloads would be required for cellulosic biofuel production relative to corn-based ethanol, thus making the per-unit cost much higher for cellulosic feedstocks then for corn. In addition, the greater number of trucks required to transport cellulosic feedstocks might also impose a heavy burden on rural transportation infrastructure.[54] Processing biomass before it goes to the plant will make it denser and less costly to transport by allowing more biomass per load (especially in the case of round bales), and it will be easier to handle once it arrives at the plant.[55] However, densification costs have been estimated at about $23 per dry ton, which may outweigh any savings related to transportation, especially if densification cannot take place immediately after harvest.[56] Densification at the storage facility would require the biomass to be transported as bales from the field and then stored until densification could take place.

Low energy density also means that a large volume of biomass would be needed by a plant to meet demand. For example, a 50 million gallon per year cellulosic ethanol plant would need a 90-feet-high pile of corn stover covering 100 acres of land in order to stay operational for a year.[57] Using a larger quantity of feedstock to make the same amount of fuel can make storage, transportation, and just-in-time delivery to plants more difficult and less efficient.

[54] C. W. Rismiller and W. E. Tyner, "Transportation Infrastructure Implications of Development of a Cellulosic Biofuels Industry for Indiana," *Journal of the Transportation Research Forum* 49(1), 2010, pp. 95-112.

[55] Petrolia (2009).

[56] Ibid.

[57] S. R. Schill, "Collecting Mountains of Stover," *Ethanol Producer Magazine*, 2007.

Harvest Timing Concerns

The timing of biomass harvest for particular feedstocks can have logistical advantages and disadvantages. For example, short-rotation woody crops can be harvested year-round, which helps ease the burden of storage because the biomass can be left on the stump until it is needed. However, the year-round harvest required to use the stump as storage may be difficult should weather or equipment failures delay any regularly scheduled harvests. In contrast, corn stover should be harvested within three weeks after corn is harvested and before any snow might cover the field, which gives it a harvest window of about five weeks to three months, depending on the location.[58] This may require additional equipment and labor so as to not interfere with the corn harvest. Perennial grasses, on the other hand, can have harvest windows of up to 8 months depending on location.[59] *Miscanthus* must be harvested after the first frost in order to take advantage of nitrogen retention through the root system.[60]

Because corn stover harvest is concentrated during one part of the year, long-term storage will be needed to hold the corn stover until the plant is ready to use it (keeping in mind that biofuels plants are designed to run year-round). For plants that can eventually use multiple feedstocks, they will be able to use corn stover around the time it is harvested, followed by feedstocks that become available at other times of the year.

Storage Concerns

Storage infrastructure for more dense crops, including grains and oilseeds, is available on many larger farms and at centralized elevator facilities. Large quantities of corn, for example, can be dried to a certain moisture content and stored for an extended period of time in a relatively small space. No such storage system or infrastructure currently exists for cellulosic biomass.

Forest biomass is attractive from a storage perspective, because it can be stored on the stump until needed and, depending on the climate and geography of its location, it can be harvested year round.[61] However, with the harvest of agricultural residues and perennial grasses being somewhat dependent on timing in the season, harvest cannot coincide with demand for biomass, which will require transportation and delivery to be tailored to the needs of the plant.

Between harvest and delivery, on-site storage of the biomass will be necessary. Storage conditions will vary from producer to producer and from region to region depending on weather conditions. While being stored, especially in outdoor condition, biomass can lose dry matter. Avoiding dry matter loss while storing biomass outside will depend on humidity and precipitation levels. Individual producers will likely be expected to store their own biomass until the plant needs it, which could be several months after it is harvested. With no central storage facility and producers not likely to have storage specifically to keep the feedstock until the plant needs it, biomass may be stored outside on the ground.

For biomass that is baled, the packaging method, whether it is with twine, net wrap, or plastic wrap, can affect the amount of dry matter loss. Ideally, corn stover bales should at least be stored on a site with good drainage, a concrete or gravel surface, and under cover or inside if not

[58] Petrolia (2009); and J. Cundiff, "Biomass Logistics in the Southeast," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009, hereafter referred to as Cundiff (2009).

[59] Cundiff (2009).

[60] S. R. Schill, "Miscanthus versus Switchgrass," *Ethanol Producer Magazine*, 2007.

[61] Cundiff (2009).

wrapped with plastic.[62] Depending on the conditions, and on assumptions regarding dry matter loss, where biomass is stored, and the form in which it is stored, storage costs will vary. A study focused on corn stover found that storage adds between $7 and $13 per dry ton.[63]

For baled biomass, the choice between round bales and square bales depends on several conditions. One study found that round bales require less expensive equipment and a lower power tractor. They can be left in the field after harvest and brought to the storage facility later. Their round tops allow water to run off, which helps decrease dry matter loss. Round bales can be stored up to six months in satellite storage locations with less than 5% loss. Cost of storage is $2 per ton for round bales compared to $8 per ton for square bales.[64] In contrast, another study found that using rectangular bales will reduce harvest and storage costs as the rectangular baler is able to bale more per hour that a round baler. However, rectangular bales have increased dry matter losses compared to round bales, so that the optimal solution may be a combination of different harvest and storage techniques.[65] **Table 14** shows estimated dry matter loss for switchgrass based on the type of bale, how it is covered, and the length of time it is stored. Each type of bale was stored on well-drained ground, gravel, and wooden pallets.[66] Overall, it is suggested that for biomass processed immediately after harvest, rectangular bales should be used, while for biomass that must be stored for more than three months, round bales with tarps should be used.

Table 14. Switchgrass Dry Matter Loss by Bale Type and Cover System

Bale Type	Cover System	100 days	200 days	300 days	400 days
Round	None	6.0%	15.7%	14.0%	9.7%
Round	Tarp	0.0%	6.1%	4.6%	7.0%
Rectangular	None	27.2%	52.5%	52.1%	64.8%
Rectangular	Tarp	25.7%	20.8%	12.5%	13.7%

Source: B. C. English and D. F. Mooney, "Economics of the Switchgrass Supply Chain: Enterprise Budgets and Production Cost Analyses," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009.

Research is being conducted to develop storage systems that keep the biomass wet while it is in storage. Biomass is mixed with additional water and made into large piles. Depending on the size of the pile, dry matter loss could be less than 5%. Advantages of a system like this include storing a given amount of biomass in a smaller area, softening biomass so as to weaken the lignin structure, and reduced risks of fire. It may also be more energy-efficient to add water than to remove it. However, as biomass is stored in such wet conditions, the bacteria that forms can consume some of the sugar that would otherwise be fermented.[67]

[62] Petrolia (2009).

[63] Ibid.

[64] Cundiff (2009).

[65] B. C. English and D. F. Mooney, "Economics of the Switchgrass Supply Chain: Enterprise Budgets and Production Cost Analyses," *Transition to a Bio Economy: The Role of Extension in Energy*, Farm Foundation Conference (Little Rock, AR), 2009, hereafter referred to as English and Mooney (2009); and C. Wang, J. Larson, B. English, and K. Jensen, "Cost Analysis of Alternative Harvest, Storage and Transportation Methods for Delivering Switchgrass to a Biorefinery from the Farmers' Perspective," selected paper, *Southern Association of Agricultural Sciences Annual Meeting* (Altanta, GA), 2009, hereafter referred to as Wang et al. (2009).

[66] Wang et al. (2009).

[67] J. W. Kram, "Search of Biomass Storage Solutions," *Ethanol Producer Magazine*, 2008, pp. 86-91.

Moisture Content Concerns

Corn stover and switchgrass are assumed to have a moisture content of around 15%.[68] Short-rotation woody crops, like poplar and willow, have about 50% moisture content at harvest.[69] In order for wood to be used for fuel, the moisture content cannot be above 65%. At this point, the energy required to dry the wood is greater than the energy content of the dry wood. The moisture content of forest residues tends to be between 40 and 60%, while the moisture content of primary mill residues, which include pulp, paper, and lumber, is around 20%, and the moisture content of secondary mill residues, which are kiln dried, is less than 10%.[70]

Quality Uniformity Concerns

Biomass can have highly inconsistent quality and characteristics, not only among feedstocks but within a feedstock type. With biomass feedstocks coming from numerous sources and producers over the course of an entire year for use at a single plant, it is initially processed so that the size will be as uniform as possible to optimize the conversion process. Plants receiving biomass that has been harvested differently and stored under a variety of conditions will incur additional costs to arrive at a uniform feedstock product.

Having a uniform feedstock delivered to the plant will decrease processing and pretreatment costs. With more experience and the development of the appropriate harvesting, collecting, and storage technologies, the pre-treatment processing step could take place before the biomass even arrives at the plant, which would eliminate the extra step and allow the plant to start with a uniform and consistent product, regardless of its source. In the case of corn stover, some processing may take place during harvest. As previously discussed, single-pass harvesting can allow stover to be chopped rather than baled. Stover in this form, however, will have high moisture content and may not be compacted.

Conclusions

The production of cellulosic feedstocks is a challenge to the development of the cellulosic biofuels industry. The establishment, maintenance, harvest, storage, and transport of cellulosic feedstocks remain far from perfect and will need to be improved in order to reduce feedstock costs. Whether the feedstock is a residue or dedicated crop, there is not much experience among producers. **Table 15** includes best-guess estimates of farm-gate feedstock costs. Transportation would also need to be added to determine the delivered cost of feedstocks, but this will depend on how far feedstocks are from the plant location. Each feedstock option is faced with opportunities

[68] Petrolia (2008); Schechinger and Hettenhaus (1999); D. A. Glassner, J. R. Hettenhaus, and T. M. Schechinger, "Corn Stover Collection Project," *BioEnergy '98: Expanding BioEnergy Partnerships*, 1998, pp. 1100-1110; J. E. Atchison and J. R. Hettenhaus, *Innovative Methods for Corn Stover Collecting, Handling, Storing and Transporting*, NREL/SR-510-33893, National Renewable Energy Laboratory (Golden, CO), March 2003; M. Khanna, B. Dhungana, and J. Clifton-Brown, "Cost of Producing Miscanthus and Switchgrass for Bioenergy in Illinois,"S *Biomass and Bioenergy*, 32(6), 2008, pp. 482-493; and D. G. Tiffany, B. Jordan, E. Dietrich, B. Vargo-Daggett, *Energy and Chemicals from Native Grasses: Production, Transportation and Processing Technologies Considered in the Northern Great Plains*, Staff Paper P06-11, University of Minnesota, Department of Applied Economics, College of Food, Agricultural & Natural Resource Sciences, 2006.

[69] G. A. Keoleian and T.A. Volk, "Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance," *Critical Reviews in Plant Sciences* 24, 2005, pp. 385-406.

[70] P. C. Badger, , *Processing Cost Analysis for Biomass Feedstocks*, ORNL/TM-2002/199, Oak Ridge National Laboratory (Oak Ridge, TN), October 2002.

to reduce production costs, and the choice of which feedstock to use will depend upon the location of the plant and the local feedstock supply availability.

Table 15. Estimated Farm Gate Cellulosic Feedstock Costs

Feedstock	Approximate Cost per Dry Ton
Switchgrass	$65 to $85
Miscanthus	$60 to $80
Corn Stover	$50 to $70
Short-Rotation Woody Crops	$50 to $60
Forest Residues	$45

Source: Estimates by Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Chapter 4: Cellulosic Biofuel Conversion Technologies

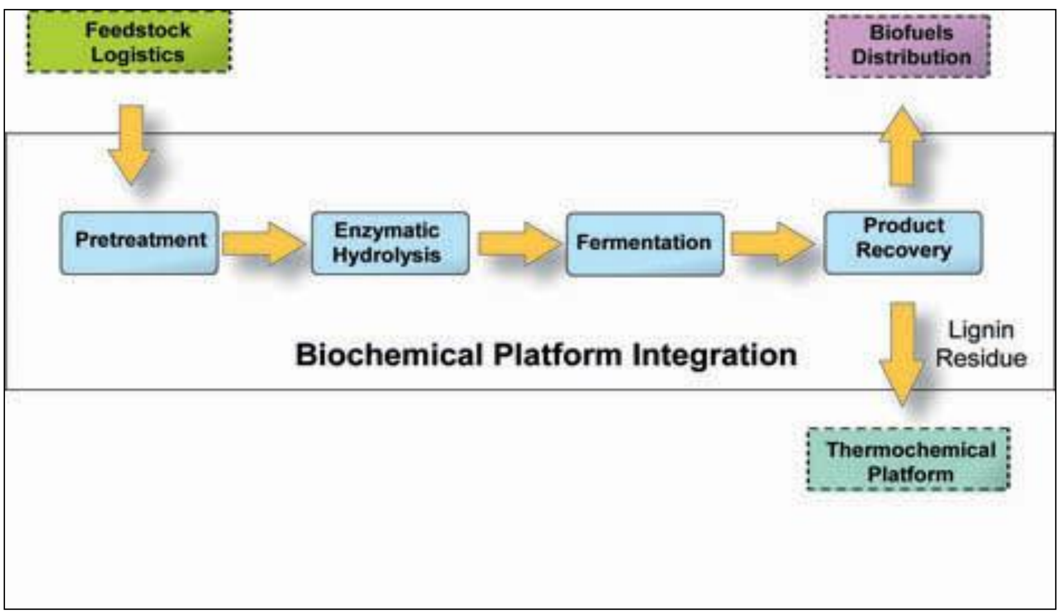
Biochemical and thermochemical conversion of lignocellulosic feedstocks are currently receiving the most attention as processing methods for cellulosic biofuels. Neither conversion process is ready for commercialization. Much of what is appearing is taking place in laboratories and demonstration and pilot plants that are small in scale. Plans for commercial plants have been announced by several companies. However, commercialization is likely to be slow to develop absent significant incentives, and cost reductions will be necessary for it to develop.

This chapter will focus on the biochemical and thermochemical conversion processes. Each process is described in some detail, and the likely areas for efficiency improvements and cost reductions are discussed. Energy yields and production costs for each process from recent studies is then presented. The current state of operational and proposed cellulosic biofuels plants is then outlined, along with a discussion of the funding thus far allocated by the federal government. Finally, there is an overview of some other developing technologies that are receiving attention as research continues to improve the efficiency of conversion processes.

Biochemical Conversion

The biochemical conversion process, as summarized in **Figure 6**, has attracted the most attention so far because of its similarities to the process currently used to produce ethanol from corn grain.

Figure 6. Biochemical Conversion Process



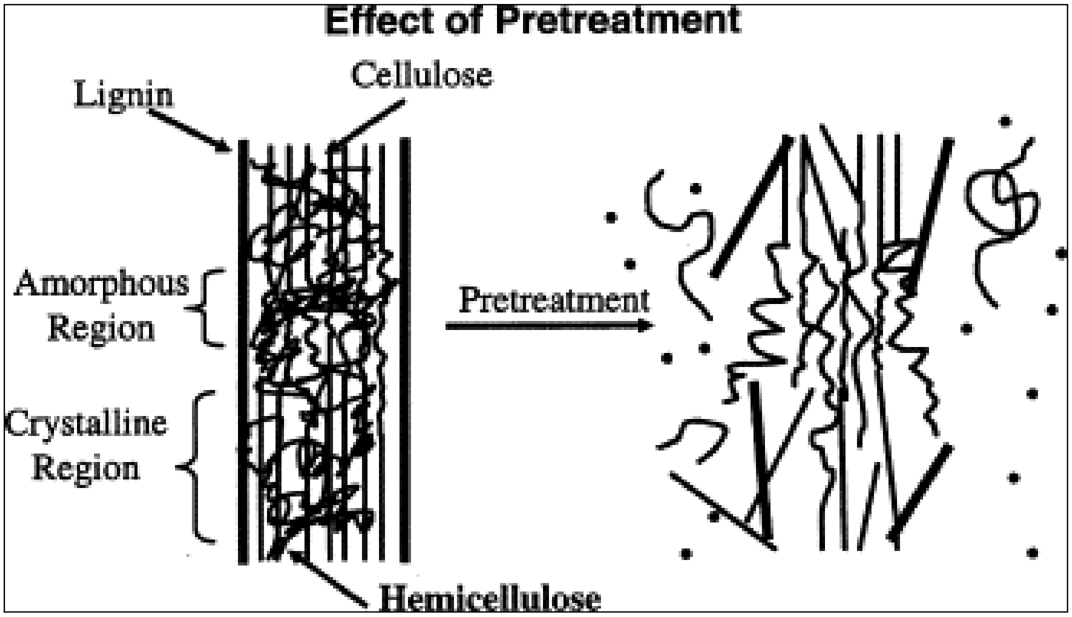
Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy, *Biomass Program*, at http://www1.eere.energy.gov/biomass/index.html.

Enzymes or acids are used to break down the plant into sugars that are then fermented into liquid fuel. Several processes are currently being researched and developed in laboratories, but it is difficult to know with any certainty whether those that appear successful in trials will also be successful on a commercial scale.

Pretreatment

The feedstock is pretreated by changing its chemical makeup in order to separate the cellulose and hemicellulose from the lignin (**Figure 7**). With the biochemical conversion process, the lignin cannot be fermented into liquid fuel, but it can be recovered for later use.

Figure 7. Simplified Impact of Pretreatment on Biomass



Source: Mosier, N., C. Wyman, B. Dale, R. Elander, Y.Y. Lee, M. Holtzapple, and M. Ladisch, "Features of promising technologies for pretreatment of lignocellulosic biomass," *Bioresource Technology* 96(6), 2005, pp. 673-686.

Reducing the lignin content of biomass or modifying it in some way are alternatives that would reduce the inputs necessary for pretreatment and enhance the effectiveness of hydrolysis. A pretreatment system should maximize the remaining amount of sugar and keep the overall process as simple as possible in order to reduce costs relative to the amount of sugar that is recovered. It is ideal for a pretreatment process to be flexible enough to handle multiple types of biomass feedstock and to reduce the preparation and processing necessary. That is, the pretreatment processes should be able to utilize many different feedstocks in a variety of forms. Pretreatment should also minimize the amount of enzymes that must be used in hydrolysis. It is estimated that pretreatment of biomass accounts for 17% of capital costs.[71]

Biological pretreatment can use fungi to change the chemical composition of the feedstock by attacking the lignin. This process, however, can take 10 to 14 days, so it is not being focused on for commercialization. Physical pretreatment will perform a mechanical breakdown of the crystalline structure to increase the surface area and make it more susceptible to attacks by enzymes or acids in later steps. The lignin is not removed with this pretreatment, and the energy inputs are presently too high for commercialization. Chemical pretreatment is used in commercial pulping processes with the goal of maintaining the overall structure of the high value pulp. With biomass, the structure should be broken down, and the pretreatment process should be less

[71] Solomon, B.D., J.R. Barnes, and K.E. Halvorsen, "Grain and cellulosic ethanol: History, economics, and energy policy," *Biomass and Bioenergy* 31, 2007, pp. 416-425.

expensive. Combination pretreatments that use both the physical and chemical pretreatment processes are being explored as an improved alternative for biomass.[72]

Hydrolysis

After sugars from the cellulose and hemicelluloses are separated and exposed during pretreatment, hydrolysis uses enzymes or acids to break down the complex chains of sugar molecules into simple sugars in preparation for fermentation. Hydrolysis will result in both glucose and xylose, which are six and five carbon sugars, respectively. Currently, enzymatic hydrolysis may be the better economic choice for commercialization relative to acid hydrolysis. Compared to acid hydrolysis, enzymatic hydrolysis is faster, more efficient, results in better yields, and uses less chemical input. Using enzymes in the hydrolysis of starch only requires one family of enzymes or cellulases. However, lignocellulosic biomass requires different cellulases to address the multiple parts of the plant.

The efficiency of hydrolysis is highly dependent on the effectiveness of pretreatment. If pretreatment leaves behind a large amount of lignin, the yield of simple sugars from hydrolysis may be reduced. The presence of lignin prevents enzymes from hydrolyzing. It is unlikely that the lignin can be completely removed from biomass, but there may be a possibility for changing some lignin characteristics in order to make it more compatible with the hydrolysis process. In the meantime, new types of catalysts that are able to deal with the lignin are being researched.

Hydrolysis can be an expensive step depending on the cost of the enzymes. These costs have definitely decreased over time but in many cases cost reduction is still a hurdle to commercialization. For a 50 million gallon per year plant, enzymes cost about 50 cents per gallon in 2009. By 2015, this cost is expected to be 44 cents per gallon.[73]

Fermentation

After pretreatment and hydrolysis have released simple sugars, fermentation is used to turn as much of that sugar as possible into liquid fuel. Hexoses, or six carbon sugars in the form of glucose, can be fermented using traditional yeast strains. Pentoses, or five carbon sugars in the form of xylose, are not fermented as easily, and research is being conducted to improve and develop microorganisms that can ferment pentose sugars. A yeast microorganism developed at Purdue University can ferment both pentoses and hexoses, which increases the ethanol yield by about 40%, and reduces costs by not requiring the sugars to be separated before fermentation.[74]

Distillation

Distillation occurs after the liquid fuel has been fermented in order to achieve a 95% pure form. Distillation is a well-established technology as it is used in corn based ethanol production.

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[72] Sims, R., M. Taylor, J. Saddler, and W. Mabee, *From 1st to 2nd Generation Biofuel Technologies: An overview of current industry and RD&D activities*, Organization for Economic Co-Operation and Development and International Energy Agency, © OECD/IEA, November 2008, [hereafter referred to as **Sims et al, OECD/IEA (2008)**].

[73] Rismiller, C.W. and W.E. Tyner, *Cellulosic Biofuels Analysis: Economic Analysis of Alternative Technologies*, Working Paper #09-06, Department of Agricultural Economics, Purdue University, 2009, [hereafter referred to as **Rismiller and Tyner (2009)**].

[74] Sedlak, M. and N.W.Y. Ho, "Production of Ethanol from Cellulosic Biomass Hydrolysate Using Genetically Engineered Saccharomyces Yeast Capable of Co-fermenting Gglucose and Xlyose," *Applicatied Biochemstry and Biotechnology*, Vol. 113-116, 2004, pp. 403-416.

Use of Lignin

Recovered lignin can be burned to generate electricity and steam to power the bio-refinery or for other outside uses. Research is being conducted to determine other ways in which the amount of lignin present in biomass can be reduced, which would help reduce the need for pretreatment.[75]

Improvements

The primary areas for potential improvement of the biochemical process are in pretreatment, hydrolysis, and fermentation. The effectiveness of pretreatment must be improved to better prepare the feedstock for hydrolysis. Enzyme costs must be reduced, and enzymes must be made more efficient. To do this, research is needed to identify and understand the inhibitors that block the breakdown of the biomass into simple sugars. Determining why lignin can resist enzymes and finding alternative uses for it will make the hydrolysis step more efficient. For fermentation, a single microorganism is needed that will ferment both five and six carbon sugars in one step. Currently, microorganisms are available to ferment each type of sugar in separate steps, but their effectiveness in an industrial capacity must still be proven. Ultimately, pretreatment, hydrolysis, and fermentation should be combined into as few steps as possible to reduce costs.

Thermochemical Conversion

Thermochemical conversion processes, which use heat to decompose the feedstock, are well established and developed. There are two main types of processes – gasification and pyrolysis. Gasification has been used primarily for converting coal into liquid fuels. The technology can also be used to convert biomass to liquid fuels. Using gasification, synthesis gas, or syngas, is produced and cleaned. The Fischer-Tropsch process is then used to convert the gas into liquid fuels of a variety of types. Using pyrolysis, a liquid bio-oil is produced and either used directly as fuel or converted into other types of fuel. Unlike biochemical conversion, thermochemical conversion uses the entire biomass including the lignin portion.

Gasification and Fischer-Tropsch Synthesis

Prior to gasification, the biomass must be 20% or less moisture. For practically any type of biomass, drying will be required. Established drying technologies usually take place at high temperatures, which creates an opportunity for improvement. Research is being done to dry biomass at lower temperatures and use excess heat from drying for other purposes.

Gasification, as summarized in **Figure 8**, is an anaerobic process where the partial combustion of biomass feedstock at over 700°C generates synthesis gas, a mixture of carbon monoxide and hydrogen.[76] Despite this being a technology already in use, producing synthesis gas from a biomass feedstock still requires improvement in cleaning up tar, ash, and other impurities in the synthesis gas that may disrupt the Fischer-Tropsch process of creating a liquid fuel by inactivating the catalyst. Fischer-Tropsch synthesis dates back to the 1920s and was used extensively by the Germans in World War II to create liquid fuel from coal.[77] Despite the

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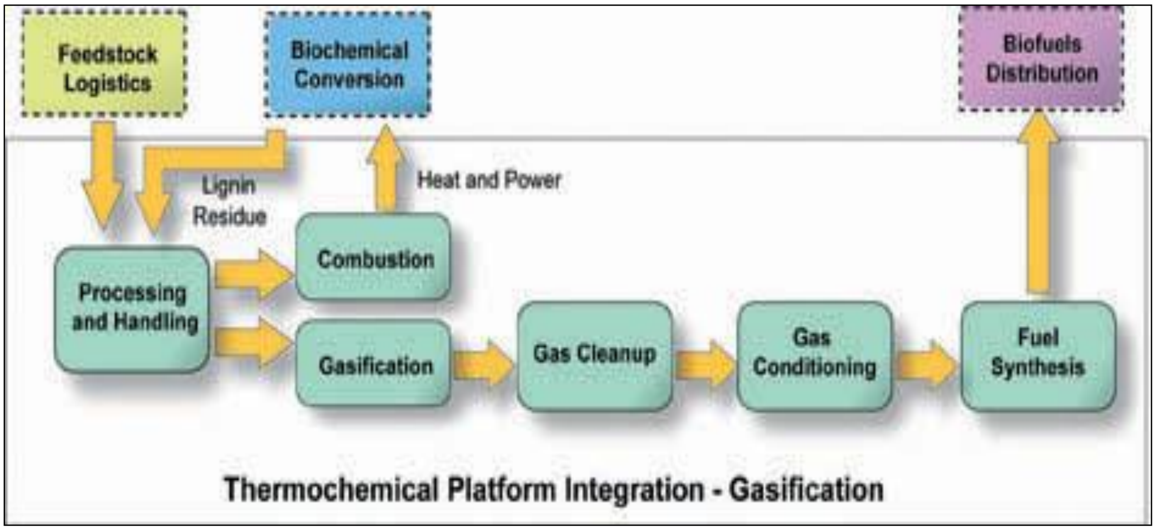
[75] Chapple, C., M. Ladisch, and R. Meilan, "Loosening lignin's grip on biofuel production," *Nature Biotechnology* 25(7), 2007, pp. 746-748.

[76] Hess, J.R., C.T. Wright, and K.L. Kenney, "Cellulosic biomass feedstocks and logistics for ethanol production," *Biofuels, Bioproducts, and Biorefining* 1, 2007, pp. 181-190; and Huber, G.W. and B.E. Dale, "Grassoline: Biofuels beyond Corn," *Scientific American*, July 2009, pp. 52-59, [hereafter referred to as **Huber and Dale (2009)**].

[77] Huber and Dale (2009).

longevity of the process, gasification to create a liquid fuel still requires further development to be commercially viable. The use of Fischer-Tropsch synthesis for liquid fuels remains on the back burner for most oil companies today and would only be used should the price of gasoline become extremely expensive.[78] Much of the current gasification technology available is used to generate power, which is similar to producing liquid fuels with respect to the catalyst used but is complicated by meeting purity standards associated with the use of biomass.

Figure 8. Thermochemical Conversion Process via Gasification



Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy, *Biomass Program*, at http://www1.eere.energy.gov/biomass/index.html.

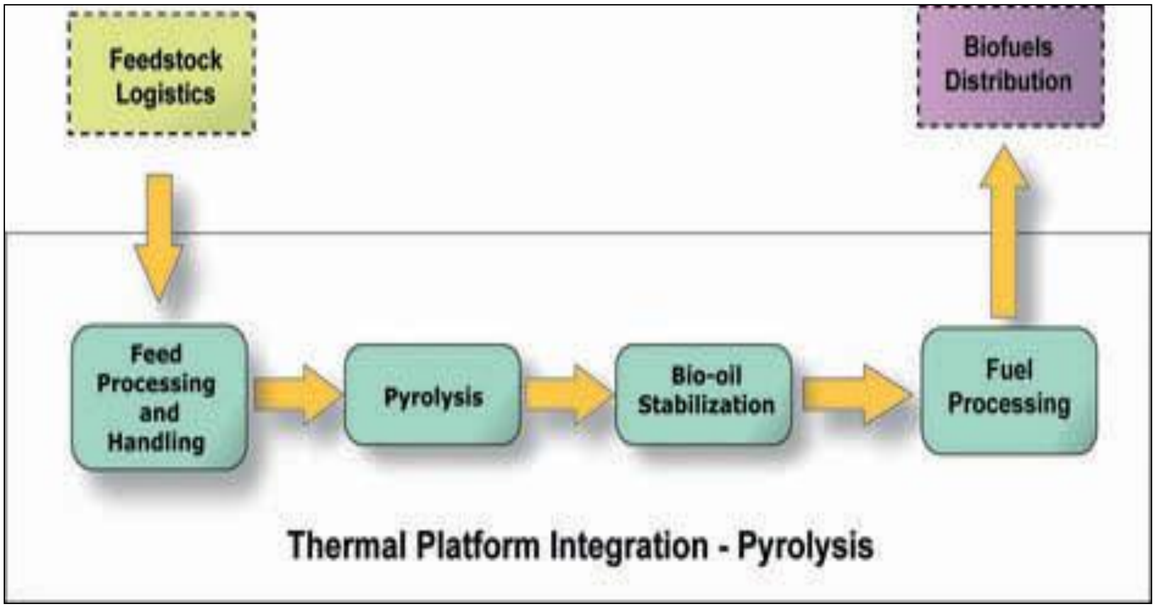
Pyrolysis

Pyrolysis, as summarized in **Figure 9**, is the partial combustion of biomass feedstock at 450°C to 600°C in the presence of no oxygen, which produces bio-oil.[79] Bio-oil, which is rich in carbon, is similar to crude oil and must be refined into biofuels. Because pyrolysis converts the biomass into a liquid form, it is easier to store and transport. Fast pyrolysis requires higher temperatures than slow pyrolysis but occurs in about two seconds. Currently, fast pyrolysis is receiving the most attention as a viable conversion process. Keeping the pyrolysis oil stable long enough to transform the bio-oil into hydrocarbons is one of the major barriers in the pyrolysis pathway.

[78] Ibid.

[79] Sims et al, OECD/IEA (2008).

Figure 9. Thermochemical Conversion Process via Pyrolysis



Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy, *Biomass Program*, at http://www1.eere.energy.gov/biomass/index.html.

Improvements

As mentioned above, thermochemical technology is already in use for the conversion of coal to gas for electricity generation. However, that technology is not currently being used to produce any liquid fuels. Gasification to produce synthesis gas also produces excess tar that is left in the gas. This excess tar requires that the synthesis gas be cleaned and conditioned. Stability of the bio-oil and cost are the major issues with pyrolysis.

Energy Yield

Another area for potential improvement relates to biofuel yield per ton of feedstock. **Table 16** outlines estimates for energy yields for both biochemical conversion and thermochemical conversion. The Department of Energy Biomass Program's Theoretical Ethanol Yield Calculator calculates the maximum theoretical yield with biochemical conversion of feedstocks based on their composition. Based on its results, the theoretical yields for corn stover, switchgrass, and forest thinning are 113, 97, and 82 gallons per dry ton, respectively (AFDC). As plants and technology approach commercialization, the rate of efficiency could approach 100% of the maximum theoretical energy yield.

Table 16. Energy Yields by Conversion Technology

Conversion Technology	Energy Yield	Expected Year
	69.7 gal./ton	2007[a]
	71.9 gal./ton	2007[b]
Biochemical (ethanol)	89.7 gal./ton	2007[a]
	78.0 gal./ton	2008[c]
	89.7 gal./ton	2015[c]

Conversion Technology	Energy Yield	Expected Year
Thermochemical	80.1 gal./ton	2007[e]
	47.0 gal./ton gasoline equivalent	2008[g]
	61.4 gal./ton	2009[h]
	94.1 gallons of mixed alcohols/ton	2015[g]

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from sources listed.

Notes: The year associated with each study is the year that this energy yield is expected to be achieved.

a. Tiffany, D.G., *Economic Comparison of Ethanol Production from Corn Stover and Grain*, Agricultural Utilization Research Institute (AURI), Energy Users Conference, (Redwood Falls, MN), March 13, 2007.

b. Aden, A., *Biochemical Production of Ethanol from Corn Stover: 2007 State of Technology Model*, NREL/TP-510-43205, National Renewable Energy Laboratory (Golden, CO), May 2008.

c. Bain, R.L., *World Biofuels Assessment, Worldwide Biomass Potential: Technology Characterizations*, NREL/MP-510-42467, National Renewable Energy Laboratory (Golden, CO), December 2007, [hereafter referred to as **Bain (2007)**]; Foust, T.D., A. Aden, A. Dutta and S. Phillips, "An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion process," *Cellulose*, 16(4), 2009, pp. 547-565, [hereafter referred to as **Foust et al (2009)**]; and Tao, L. and A. Aden, "The economics of current and future biofuels," *Vitro Cellular and Developmental Biology*, 45(3), 2009, pp. 199-217, [hereafter referred to as **Tao and Aden (2009)**].

d. NAS, Liquid Transportation Fuels from Coal and Biomass (2009).

e. Rismiller and Tyner (2009).

f. Bain, R.L. (2007); Foust et al (2009); and Tao and Aden, (2009).

g. NAS, Liquid Transportation Fuels from Coal and Biomass (2009).

h. Wright, M.M. and R.C. Brown, "Comparative Economics of Biorefineries based on the Biochemical and Thermochemical Platforms," Biofuels, Bioproducts, and Biorefining 1 (2007), pp. 49-56, [hereafter referred to as **Wright and Brown (2007)**]; as taken from Rismiller and Tyner (2009).

i. Bain (2007) as taken from Rismiller and Tyner (2009).

Estimated Cost per Gallon

Considering that the production of cellulosic biofuels is in its infancy, predictions of the total cost are subject to a high degree of uncertainty. Most research in the area is focused on cost reduction, so up-to-date cost estimates can quickly become inaccurate with improvements to feedstocks and conversion technologies. **Table 17** outlines estimates from recent studies for total capital costs and operating costs per gallon for biochemical conversion.

Table 17. Biochemical Production Costs

Plant Size (MGPY)	Capital costs: $ Million ($/gal.)	Capital charge ($/gal.)	Operating costs ($/gal.) in gasoline equivalent: Feedstock, Energy, Enzyme, Other Variable Costs	Total Cost ($/gal.)	Data Year
25	$136 ($5.44)	$0.73	$1.50 x 1.5 = $2.25[a]	$2.98	1999[b]
45	$183 ($4.06)	$0.54	$1.48 x 1.5 = $2.22	$2.76	2007[c]
50	$338 ($6.76)	$0.91	$1.97	$2.88	2009[d]
69.3	$220 ($3.17)	$0.43	$1.33[e] x 1.5 = $2.00	$2.43	2007[f]
100	$349 ($3.49)	$0.79	$1.97	$2.76	2009[g]
150	$756 ($5.04)	$0.67	$1.76	$2.43	2005[h]

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

Notes: MGPY = Million gallons per year. "Capital costs" per annual gallon are included in order to compare capital expenses for plants of various sizes. The "Capital charge" per gallon is estimated using an annual payment calculated at a 12% interest rate for a plant with a life of 20 years. The "Total Cost" per annual gallon equals the sum of the capital charge (per gallon) and operating costs (per gallon).

a. Prices published as $ per gallon of ethanol (volumetric basis) were multiplied by 1.5 in order to convert to $ per gallon of gasoline energy-equivalent basis.

b. McAloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley, *Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks*, NREL/TP-580-28893, National Renewable Energy Laboratory, (Golden, CO), October 2000.

c. Tao and Aden (2009)

d. Rismiller and Tyner (2009).

e. $1.33 per gallon is the minimum ethanol selling price.

f. Foust et al (2009).

g. NAS, *Liquid Transportation Fuels from Coal and Biomass* (2009).

h. Wright and Brown (2007).

Table 18 summarizes capital and operating costs for thermochemical conversion. The estimates vary based on the year they were conducted and the size of the plant. One study found that there is no distinct economic difference between biochemical and thermochemical conversion for cellulosic ethanol production.[80] The same study found that herbaceous feedstocks are better suited for biochemical conversion, while woody biomass is better suited for thermochemical conversion.[81]

Table 18. Thermochemical Production Costs

Plant size MGPY	Capital costs $ Million ($/gal.)	Capital charge ($/gal.)	Operating costs ($/gal.) in gasoline equivalent: Feedstock, Energy, Enzyme, Other Variable Costs	Total Cost ($/gal.)	Data Year
45	$241 ($5.36)	$0.72	$1.32 x 1.5 = $1.98[a]	$2.70	2007[b]
45	$488 ($10.84)	$1.45	$1.70	$3.15	2009[c]
61.8	$210 ($3.17)	$0.42	$1.22[d] x 1.5 = $1.83	$2.28	2007[e]
67	$636 ($9.49)	$1.27	$1.78	$3.05	2008[f]
150	$854 ($5.69)	$0.76	$1.80	$2.56	2007[g]

Source: Compiled by Tyner, Brechbill, and Perkis, Purdue University, August 2010, from listed sources.

Notes: MGPY = Million gallons per year. "Capital costs" per annual gallon are included in order to compare capital expenses for plants of various sizes. The "Capital charge" per gallon is estimated using an annual payment calculated at a 12% interest rate for a plant with a life of 20 years. The "Total Cost" per annual gallon equals the sum of the capital charge (per gallon) and operating costs (per gallon).

a. Prices published as $ per gallon of ethanol (volumetric basis) were multiplied by 1.5 in order to convert to $ per gallon of gasoline energy-equivalent basis.

b. Tao and Aden (2009).

c. Rismiller and Tyner (2009).

d. $1.22 per gallon is the minimum ethanol selling price.

e. Foust et al, *Cellulose* (2009).

f. NAS, *Liquid Transportation Fuels from Coal and Biomass* (2009).

[80] Foust et al (2009)

[81] Ibid.

g. Wright and Brown (2007).

Current Plants

There are currently no commercial cellulosic biofuel plants in the United States, and plans for proposed plants are far from definite. However, as of April 2009, there were 25 operational pilot and demonstration cellulosic ethanol plants with approximately 3.5 million gallons of ethanol production capacity.[82] Of these plants, 17 are using biochemical conversion technology, seven are using thermochemical conversion technology, and one is using a combination of both technologies. These pilot and demonstration plants are using a wide range of feedstocks including corn stover, wheat straw, rice straw, sugarcane bagasse, switchgrass, wood residues, paper waste, and municipal solid waste. These plants are run by a combination of academic, government, and private organizations. Three plants are currently under construction and were expected to be operational by the end of 2009, but none achieved the objective.[83] These three plants, once operable, are expected to produce a combined total of over 10 million gallons of ethanol annually. Other planned or proposed plants are often quite small due to uncertainties regarding conversion technology and limits to funding.

According to *Ethanol Producer Magazine,* which maintains a list of proposed ethanol plants (include both corn and cellulosic plants in the United States and Canada), estimated that there were 118 proposed plants in 2008, but only 70 proposed plants in 2009.[84] Of those proposed in 2009, 30 planned to use cellulosic feedstocks and would produce just over one billion gallons per year if constructed according to proposed dimensions. However, the 40% decline in the number of proposed plants from 2008 to 2009, is indicative of how much uncertainty exists in predicting when future biofuels plants will begin construction, let alone when they will reach commercialization. It is likely that some of the decline is be attributed to difficulty securing financing in the fragile financial markets and to uncertainty in oil and corn prices.

Between 2002 and 2008, the Department of Energy's Energy Efficiency and Renewable Energy Biomass Program allocated more than $800 million in federal funding to both private companies and universities for advanced biofuels research and development. An additional $786.5 million from the American Recovery and Reinvestment Act (P.L. 111-5) has been slated to provide added funding for development of commercial sized bio-refineries.[85]

Table 19 describes 10 plants that are receiving DOE or USDA support. In total, including these 10 plants, there are 16 planned cellulosic ethanol plants and 22 proposed cellulosic ethanol plants with a total annual production capacity of 639 million gallons.[86] Many of these plants are in the planning stages of conducting feasibility studies and securing funding and necessary permits. It is uncertain whether all of these plants will actually be constructed and become operational, but further research with DOE funded projects should increase the chance of success. The six plants that initially received $385 million in DOE funding in February 2007 were originally expected to

[82] U.S. EPA (2009), Table 1.5-33, p.165.

[83] Ibid.

[84] Skauge, M., et al., "Proposed Ethanol Plant List 2009: United States and Canada," *Ethanol Producer Magazine*, April 2009.

[85] Christiansen, R.C., "The Cellulosic Ceiling," *Ethanol Producer Magazine*, August, 2009.

[86] U.S. EPA (2009), Table 1.5-36 and Table 1.5-47, pp. 172-173.

be operational by 2011.[87] However, several of the plants have either postponed or cancelled their plans to proceed with construction (including Alico, Iogen, and Mascoma).[88]

Table 19. Cellulosic Ethanol Plants Receiving DOE or USDA Support

Company	Loc-ation	Feedstocks	Production Capacity: MGPY	Estimated Operating Date	Conversion Technology	DOE Funding ($ Mln)	Federal Loan Guarantee
Abengoa Bioenergy Corp.	KS	Corn stover, wheat straw, milo stubble, switchgrass	11.4	2012	Biochemical	$76	
BlueFire Mecca, LLC	CA	Woodchips, grass cuttings, other yard waste	17.0	TBD	Biochemical	$40	DOE
Ecofin/Alltech	KY	Corn cobs	1.3	2010	Biochemical	$30	
ICM Inc.	MO	Corn fiber/stover, sorghum, switchgrass	1.5	2010	Biochemical	$30	
Mascoma Corp.	MI	Wood fiber	40.0	2012	Biochemical	$26	
Pacific Ethanol	OR	Wheat straw, wood chips, corn stover	2.7	TBD	Biochemical	$24	
POET Project Liberty	IA	Corn cobs/fiber	25.0	2011	Biochemical	$80	DOE
Range Fuels	GA	Wood waste, switchgrass	40.0	2011	Thermo-chemical	$76	USDA
RSE Pulp and Chemical	ME	Woody biomass	2.2	2010	Biochemical	$30	
Verenium Corp.	LA	Sugarcane bagasse, wood, energycane	1.5	Online	Biochemical	$10	

Source: U.S. EPA (2009), Table 1.5-35, p. 170.

Notes: MGPY = million gallons per year. Mln = million.

Other Technologies

BP and DuPont have entered into a partnership to research and develop biobutanol (which has an energy content just a bit less than gasoline), rather than ethanol.[89] Under current technology, biobutanol is more expensive to produce than ethanol; however, it has several inherent

[87] Ebert, J., "Cellulosic Ethanol Path is Paved with Various Technologies," *Ethanol Producer Magazine*, July 2008.

[88] DTN *Ethanol Blog*, "Mascoma's Cellulosic Ethanol Plan Likely Delayed," May 25, 2010; and "Iogen Suspends U.S. Cellulosic Ethanol Plant Plans," By Katie Fehrenbacher, gigaom.com, Jun. 4, 2008.

[89] BP and DuPont, "Biobutanol fact sheet," BP-Dupont biofuels fact sheet, June 2006.

characteristics that make it a preferred transportation fuel over ethanol. Both first generation and second generation feedstocks can be used to produce biobutanol, which can easily be blended with gasoline. It can be blended at higher concentrations to avoid problems with the blending wall that currently face ethanol production. Biobutanol is easier to distribute than ethanol (given the current gasoline pipeline infrastructure). It can likely be shipped in existing pipelines and is less likely to separate in the presence of water than ethanol. After a few years of research and development, the BP and DuPont partnership is currently working on a demonstration plant and looks to have its first commercial plant operating by 2013.[90]

Researchers at Purdue University have developed new thermochemical processes that involve adding externally produced hydrogen to either a pyrolysis process or gasification process to enable capturing more of the carbon content in the cellulosic biomass.[91] This could increase the efficiency of the entire conversion process by possibly producing three times as much biofuels from the same quantity of biomass. While this process would reduce the amount of land needed to produce a given volume of biofuels, a cost-effective source of hydrogen must be secured. Researchers are focusing on a carbon-neutral hydrogen source like nuclear, wind, or solar for the long term and natural gas for the short term.

Conclusions

In order for cellulosic biofuels to be commercialized, the cost per gallon for conversion must be reduced, regardless of the conversion technology used, and the entire process must be made more efficient by increasing the biofuel yield per ton of feedstock. Biochemical and thermochemical conversion technologies are receiving the most attention for cellulosic biofuels production. Most of the development of cellulosic conversion technology is happening on a laboratory scale or in small demonstration or pilot plants. For the biochemical process, the sugars in cellulosic feedstocks must be broken down and separated before being converted into biofuels. This complex and rigid structure presents a challenge for cellulosic biofuels that is not faced by corn-based ethanol. Enzyme costs appear to be an important limiting factor for biochemical conversion. For thermochemical conversion, the higher capital cost is the major barrier to overcome. New cellulosic plants are receiving funding from DOE and USDA, but feedstock and conversion cost reduction will be the ultimate test for whether the cellulosic biofuels industry will achieve commercialization and be able to meet standards set by the Renewable Fuel Standard for advanced biofuels.

[90] BP and DuPont, "Butamax Advanced Biofuels LLC," BP-Dupont biofuels fact sheet, undated.

[91] Agrawal, R., N. Singh, F. Ribeiro, and W.N. Delgass, "Sustainable fuel for the transportation sector," Proceedings of the National Academy of Sciences (PNAS), 104(12), March 2007, pp. 4828-4833.

Chapter 5: Economics and Policy of Cellulosic Biofuels

This final chapter of this report will look at some of the main government policies that are likely to impact the progress of cellulosic biofuels. After a brief review of policy and market developments, there is a discussion of the blend wall, its impact on the growth of biofuels in the United States, and some possible solutions to the challenges of the blend wall. Then, the Renewable Fuel Standard and the Biomass Crop Assistance Program (BCAP) are summarized. This is followed by a comparative discussion of fixed versus variable biofuels subsidies . Finally, the potential effects of fixed and variable subsides are evaluated using a plant-level cost model with both biochemical and thermochemical conversion processes and stochastic input prices.

Introduction

The United States has been the world's leading producer of ethanol since 2005 when it surpassed Brazil.[92] The biofuels industry began in the United States with corn-based ethanol in the late 1970s, and grew slowly until the oil price run-up of 2005 accelerated industry investment and growth (**Figure 10**). From the beginning, ethanol blending has been subsidized in the form of a tax credit at a rate of between 40 and 60 cents per gallon. Other supportive policies have been added in recent years, but the blending tax credit has been paramount from the beginning.[93]

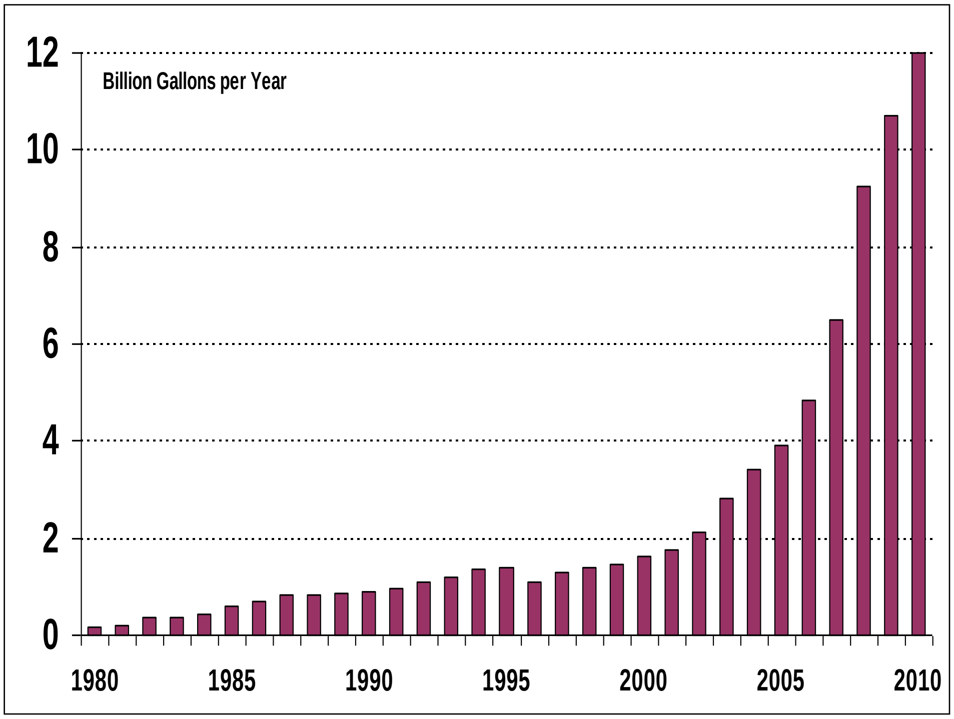
Over the period 1983 to 2003, the price of oil averaged about $20 per barrel. When coupled with the blending tax credit and mandates for the use of oxygenates (including ethanol) in reformulated gasoline following the 1990 Clean Air Act Amendments, $20 oil was enough to promote slow, but steady growth of the U.S. corn ethanol industry.[94] Over this period, the price of ethanol varied but generally was equal to the gasoline price plus the government subsidy (**Figure 11**). That is, pricing was on a pure volumetric basis. Ethanol had value both as an oxygenate and for its higher octane level. Then in 2004 the price of oil began its move up, and the combination of a fixed subsidy keyed to $20 oil and much higher oil prices caused a boom in the corn ethanol industry. With high oil prices and substantial fixed subsidies, the ethanol industry enjoyed large profits and significant investment in new plants through 2007. The price relationship between ethanol and gasoline also became much more volatile as the quantity of ethanol on the market increased and other factors (such as the widespread phase out by May 2006 of MTBE, a major oxygenate competitor) came into play.

[92] CRS Report R41282, *Agriculture-Based Biofuels: Overview and Emerging Issues*, by Randy Schnepf.

[93] In addition to the blending tax credit, the U.S. biofuels industry is supported by an import tariff on foreign-produced ethanol (started in 1980), a mandated blending-use requirement (started in 2006) that expands rapidly to 36 billion gallons by 2022, and several loan, loan guarantee, and grant programs designed to facilitate growth in production and use of biofuels. For more information see CRS Report R40110, *Biofuels Incentives: A Summary of Federal Programs*, by Brent D. Yacobucci

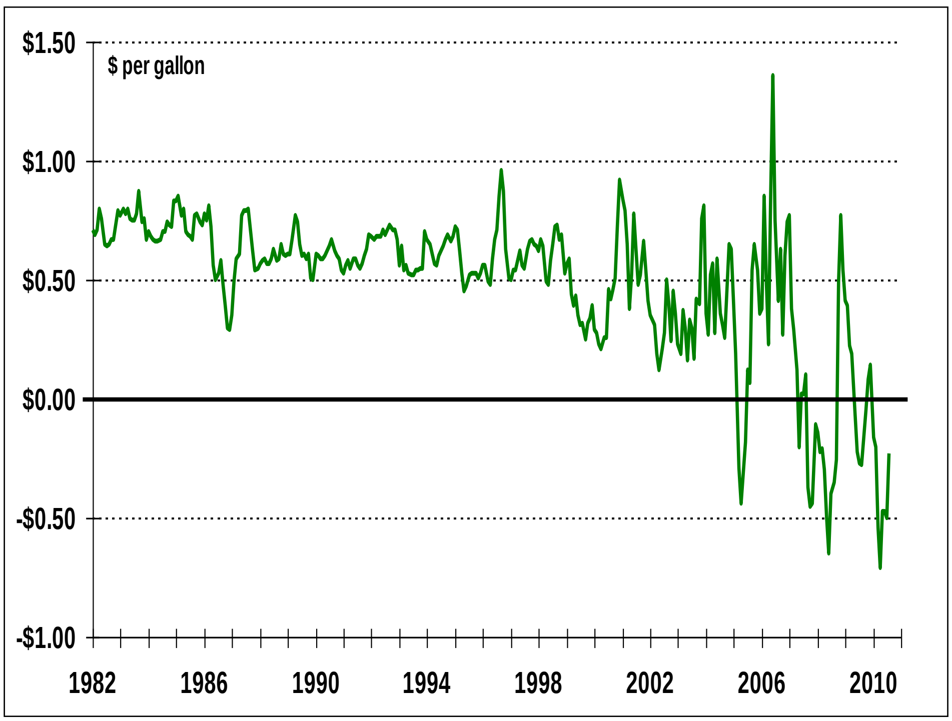
[94] Tyner, W.E., "The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects," *BioScience* 58(7), 2008, pp. 646-653, [hereafter referred to as **Tyner, *Biofuels Origins and Prospects*, (2008)**].

Figure 10. U.S. Ethanol Production from 1980 to 2010



Source: 1980 to 2009, Renewable Fuel Association; 2010 is projected by the authors.

Figure 11. Historic Ethanol and Gasoline Price Differences



Source: Nebraska Ethanol Board, Lincoln, NE.

Notes: Prices are monthly average rack prices for ethanol and 87 octane, unleaded gasoline , Omaha, NE.

Beginning in 2008 the corn ethanol industry faced major economic difficulties as the price of corn surged. Corn is the single largest cost component in ethanol production accounting for nearly 66% of input costs.[95] Over two billion gallons of production capacity was shut down. Then even after corn prices fell, capacity remained down because the industry had reached the effective blend wall by mid-2009. The blend wall refers to the maximum quantity that can be blended given the 10% blending rate (more on this topic below). With excess supply on the market, the price of ethanol was ultimately forced down to the break-even price with corn. Conditions improved in late 2009 and early 2010 as more ethanol could be blended in winter months. However, in the spring of 2010, the industry returned to effectively operating at the blend wall. So long as the blending wall remains binding, this situation will persist.

The future of cellulosic biofuels and the potential to be profitable will depend a great deal on cost reductions in feedstock production and conversion technology, as discussed in the previous section. The economic situation and the policies implemented to support cellulosic biofuels will likely play a critical role in determining the path of commercialization just as they did for corn ethanol.

Blend Wall

The blend wall is a physical limit on the volume of ethanol that can be blended into the national transportation fuel supply due to the regulatory limit of 10% ethanol in fuel blends for standard vehicles.[96] As of August 2010, 10% was the national blending level. This blending limit was partially modified on October 13, 2010 (discussed below) to allow 15% blends for use in model 2007 and newer light-duty vehicles.

With annual U.S. gasoline consumption of about 140 billion gallons, the maximum amount of ethanol that can be blended to make E10 (90% gasoline and 10% ethanol) is 14 billion gallons.[97] To achieve 14 billion gallons of ethanol would require that every gallon of gasoline used across the country be blended at a 10% level. However, it is not possible to blend at that level everywhere. California has had a lower blending limit. In the South, blending has not been common in summer months because of higher evaporative emissions. There are problems with distribution to some regions. A more realistic estimate of the current blend wall is around 12 billion gallons or 9% of gasoline consumption.[98] **Figure 12** shows how U.S. ethanol consumption is converging with the amount of ethanol that would be needed if all gasoline were blended at a rate of 10%. This chart shows that gasoline use has only increased slightly over the past 15 years, but ethanol consumption has increased dramatically, especially over the past five years.

More ethanol use is possible with an increase in E85 (15% gasoline and 85% ethanol) consumption. However, E85 pumps are in short supply throughout the country and will likely not increase without strong government intervention.[99] The number of flexible fuel vehicles (FFVs)

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[95] Shapouri, H., and P. Gallagher, *USDA's 2002 Ethanol Cost-of-Production Survey*, AER 841, Office of the Chief Economist, USDA, July 2005.

[96] CRS Report R40155, *Renewable Fuel Standard (RFS): Overview and Issues*, by Randy Schnepf and Brent D. Yacobucci.

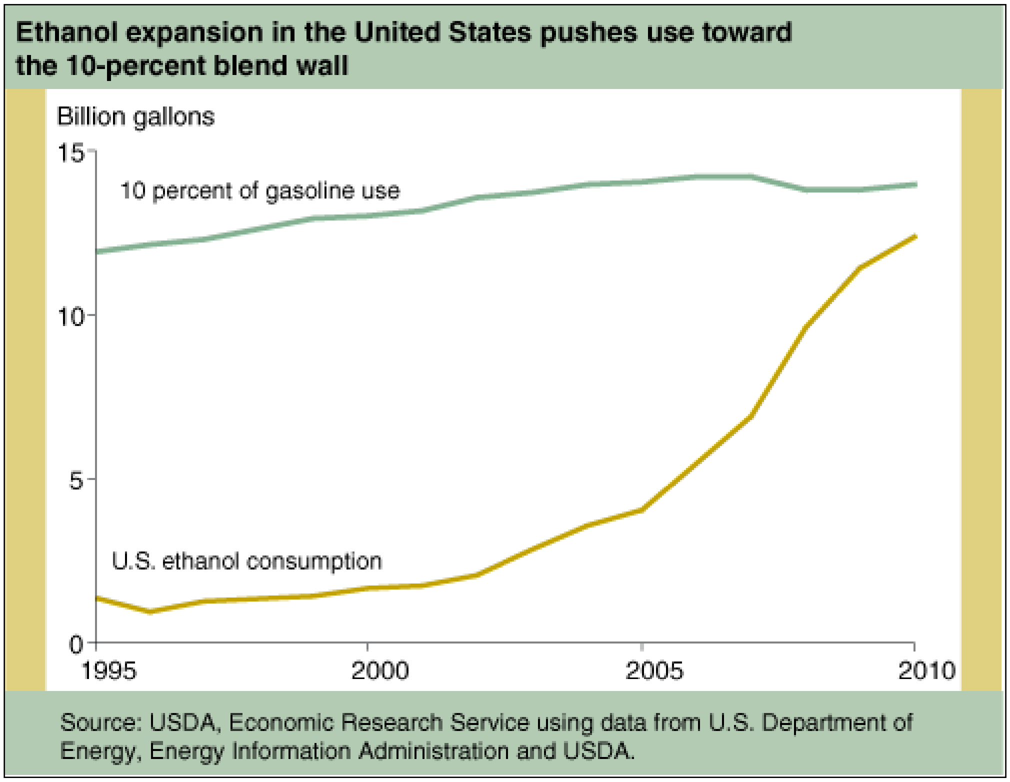
[97] Tyner, W. and D. Viteri, "Implications of Blending Limits on the US Ethanol and Biofuels Markets," *Biofuels* 1(2), 2010. pp. 251-253, [hereafter referred to as **Tyner and Viteri (2010)**]; and Tyner, W.E., F. Taheripour, and D. Perkis, "Compariosn of Fixed versus Variable Biofuels Incentives," *Energy Policy*, 38(10), October 2010, pp. 5530-5540, [hereafter referred to as **Tyner, Taheripour, and Perkis (2010)**].

[98] Tyner, W.E., F. Dooley, C. Hurt, and J. Quear, *Ethanol Pricing Issues for 2008, Industrial Fuels and Power*, February 2008, pp. 50-57; and Tyner and Viteri, (2010).

[99] Tyner, W.E., F. Dooley, and D. Viteri, "Effects of Biofuel Mandates in a Context of Ethanol Demand Constraints,

in the United States capable of running on E85 is estimated at over 8 million as of mid-2010,[100] but this accounts for only about 3% of the 240 million cars, vans, and light trucks that make up the nation's vehicle fleet.[101] Furthermore, very few of these are running on E85 even part of the time. If all 8 million FFVs ran exclusively on E85, they would consume an additional 4.7 billion gallons of ethanol (assuming 12,000 miles/vehicle-year and 20 mpg on ethanol). Currently, less than 0.5% of total U.S. gasoline consumption is in the form of E85.[102]

Figure 12. U.S. Ethanol Consumption and the 10% Blend Wall



Source: Westcott, P.C., "Full Throttle U.S. Ethanol Expansion Faces Challenges Down the Road," *Amber Waves*, September 2009.

An option for solving the blend wall is to increase the rate at which ethanol is blended with gasoline in conventional vehicles to 15% or 20% to increase the total amount of ethanol that can be used in the gasoline consumed by the conventional vehicle fleet. DOE and EPA are conducting tests to see whether higher blends will be compatible with current vehicles that run on conventional gasoline.[103] There is concern that newer vehicles with warranties may see those warranties voided if higher blends are used. In 2010, Underwriter's Laboratories (UL) certified

Cellulosic Biofuel Costs, and Compliance Mechanisms," *American Journal of Agricultural Economics* 92(5), 2010, [hereafter referred to as **Tyner, Dooley, and Viteri (2010)**].

[100] Renewable Fuel Association, "E85," at http://www.ethanolrfa.org/pages/e-85.

[101] Tyner, Dooley, and Viteri (2010).

[102] DOE, EIA, *Alternatives to Traditional Transportation Fuels 2008*, Table C1. Estimated Consumption of Vehicle Fuels in the United States, by Fuel Type, 2004 – 2008.

[103] CRS Report R40445, *Intermediate-Level Blends of Ethanol in Gasoline, and the Ethanol "Blend Wall"*, by Brent D. Yacobucci.

that current gasoline dispensing equipment can handle blends containing up to 15% ethanol.[104] However, UL also said that E15 would not be suitable because, if one assumes that E10 may have some 15% ethanol, then some E15 will almost certainly have higher than 15% ethanol which may prove harmful to existing distribution infrastructure.

In March 2009, Growth Energy, representing ethanol producers, applied for a waiver from the Environmental Protection Agency to increase the blending rate from 10% to 15%. On October 13, 2010, EPA issued a partial waiver for gasoline that contains up to a 15% ethanol blend (E15) for use in model year 2007 or newer light-duty motor vehicles (i.e., passenger cars, light-duty trucks, and sport utility vehicles).[105] A decision on the use of E15 in model year 2001 to 2006 vehicles will be made after EPA receives the results of additional DOE testing, possibly as early as November 2010. However, EPA also announced that no waiver would be granted for E15 use in model year 2001 and older light-duty motor vehicles, as well as in any motorcycles, heavy duty vehicles, or non-road engines. In addition to the EPA waiver announcement, numerous other changes have to occur before gas stations will begin selling E15 including many approvals by states and significant infrastructure changes (e.g., labeling of pumps, storage tanks, etc.). As a result, the vehicle limitation to newer models, coupled with infrastructure issues, are likely to limit rapid expansion of blending rates.

Discussions of the blend wall have applied largely to the already established corn ethanol industry. However, with the eventual onset of commercial cellulosic biofuel production and a Renewable Fuel Standard that will require biofuels made from feedstocks other than corn, the issue of the blend wall and the current 10% blending rate may serve to hinder or even stop the development of the cellulosic biofuels industry before it gets started.[106] With mandated biofuels amounts higher than what can possibly be blended, the RFS may need to be capped and revised from its legislated levels.[107]

In effect, the blend wall is a constraint on the amount of ethanol that can be absorbed by the market. The presence of the blend wall serves to make the demand curve vertical, such that the same quantity of ethanol is demanded regardless of the price, once the blend wall quantity is achieved. The blend wall limits demand of ethanol to an amount that is less than the equilibrium amount (where ethanol supply equals unconstrained ethanol demand). This creates a market with reduced ethanol demand, excess ethanol supply, and an artificially low ethanol price and explains why some of the U.S. corn-based ethanol capacity was shut down in 2008 and 2009, and even through 2010.[108]

Figure 13 shows the effect on the ethanol market of a blend wall. The fixed subsidy is also shown through the shift to the right of the demand curve. With a subsidy, more ethanol will be demanded at any given price. In **Figure 13**, the intersection between the supply curve and the demand curve with the subsidy indicates the quantity and price (P*) that would result without the blend wall. However, when the blend wall is in effect, the demand curve becomes vertical once that quantity (Q^{BW}) is reached. This demand curve with the blend wall is the bold line in **Figure 13**. The outcome will then be the intersection between the supply curve and the demand curve with the

[104] Ibid.

[105] EPA, "EPA Grants E15 Partial Waiver Decision and Fuel Pump Labeling Proposal," EPA420-F-10-054, October, 2010. at http://www.epa.gov/otaq/regs/fuels/additive/e15/420f10054.htm.

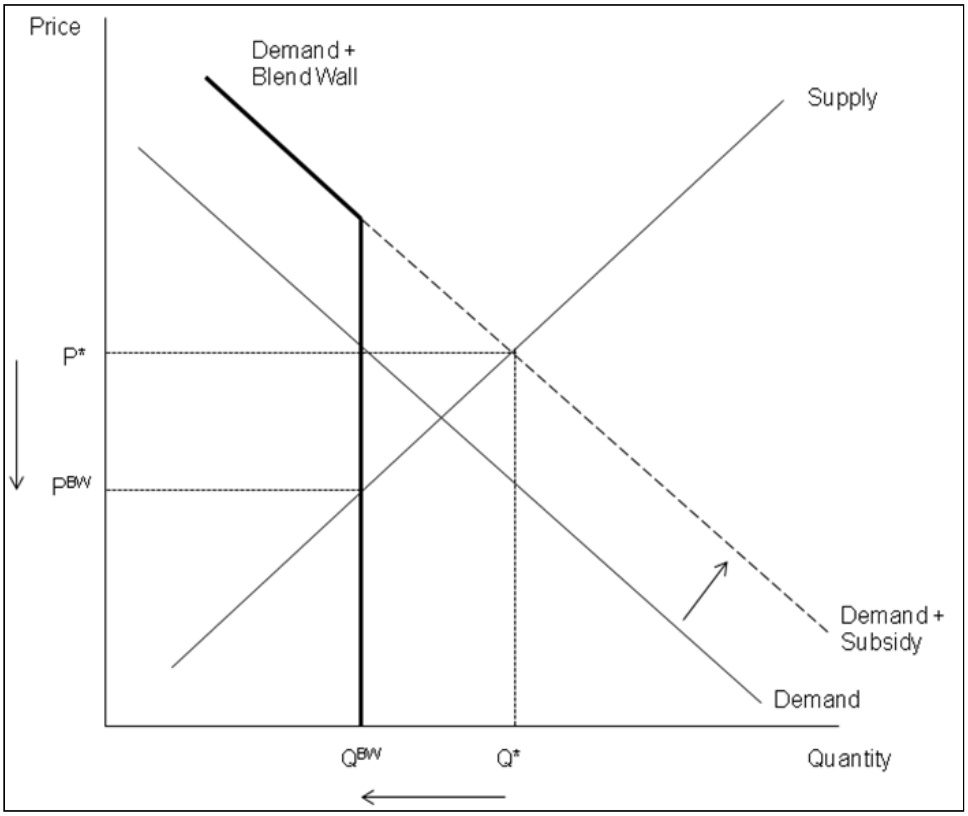
[106] Tyner and Viteri (2010), and Tyner, Dooley, and Viteri (2010).

[107] Tyner and Taheripour (2008).

[108] Tyner, Taheripour, and Perkis (2010).

blend wall. Relative to the case where the blend wall is not in effect, the amount of ethanol consumed will decrease to the blend wall (Q^{BW}) and the ethanol price (P^{BW}) will also decrease.

Figure 13. Ethanol Subsidies and the Blend Wall



Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

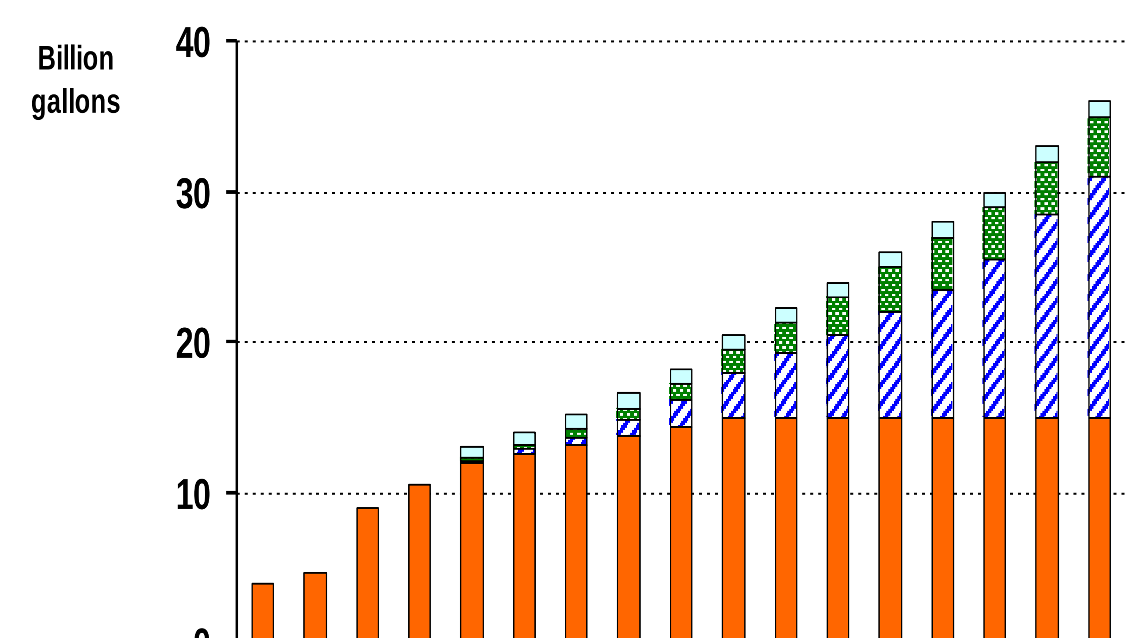
If EPA determines to maintain the blend level at 10%, it will not be possible for cellulose ethanol to become established. Corn ethanol will be less expensive under most foreseeable conditions, so there would not be investment in cellulose ethanol even with the cellulose-based RFS. The perceived uncertainty would be too large to elicit industry investment. However, cellulosic-based biofuels produced via thermochemical conversion (e.g., bio-butanol) could be developed because they are not affected by the blend wall. These synthetic petroleum products can be used by existing petroleum-based distribution and storage infrastructure and the current fleet of U.S. vehicles.

However, even if the blending limit is increased to 15%, there still may not be room for much cellulose ethanol. From the description of the RFS below, one can see that in 2022 the corn (or conventional) component is 15 billion gallons, and the other "advanced biofuels" part is 4 billion. Sugarcane ethanol is included in the other advanced category. So corn plus sugarcane ethanol could sum to as much as 19 billion gallons. As noted above, 19 billion gallons is the effective blend wall at 15% blending. Since corn and sugarcane ethanol are likely to always be less expensive to produce than cellulosic ethanol, they could crowd out cellulosic ethanol even at the 15% blending level. Again, synthetic hydrocarbons produced via the thermochemical pathway would not be affected by the blend wall.

Renewable Fuel Standard

The Renewable Fuel Standard (RFS) was first introduced as a part of the Energy Policy Act of 2005 (P.L. 109-58). It required that 4 billion gallons of renewable fuels be used starting in 2006, increasing to a 7.5-billion-gallon requirement in 2012. The original RFS was never binding, meaning that the market always produced a quantity larger than the level of the mandate. The RFS was increased dramatically in the Energy Independence and Security Act of 2007 (EISA; P.L. 110-140). In 2008, 9 billion gallons of renewable fuels were required, and this requirement increases to 36 billion in 2022. There are also requirements as to what fraction of the total mandate must come from various types of fuels. **Figure 14** outlines the timing and break down of the requirements for the RFS.

Figure 14. U.S. Renewable Fuel Standard (RFS) Mandates by Biofuel Type



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Biomass-based Diesel					0.7	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Non-cellulosic Advanced					0.2	0.3	0.5	0.8	1.0	1.5	2.0	2.5	3.0	3.5	3.5	3.5	4.0
Cellulosic Advanced					0.1	0.3	0.5	1.0	1.8	3.0	4.3	5.5	7.0	8.5	10.5	13.5	16.0
Corn-starch Ethanol	4.0	4.7	9.0	10.5	12.0	12.6	13.2	13.8	14.4	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0

Source: Energy Independence and Security Act of 2007, (EISA; P.L. 110-246)

Note: After 2012, the 1.0 billion gallons of biomass-based diesel is a lower limit. EPA can set the mandate higher, and reduce the "unspecified advanced biofuel" portion by an equal amount.

The primary feature of the updated RFS is that it limits the amount of biofuels that can be produced from corn and still qualify under the RFS, and requires greenhouse gas (GHG) emission reductions relative to emissions from conventional gasoline for RFS-qualifying biofuels. From 2010 until 2015, the corn-based biofuels cap only increases slightly under the RFS, and eventually levels off in 2015 at 15 billion gallons. Any production of corn-based biofuels beyond this level will not count towards the mandate. For any corn-based ethanol from new refineries to count, it must reduce GHG emissions by 20% compared to conventional gasoline. However, all plants in production or under construction as of December 2007 are grandfathered—and that is most, if not all, of the eventual 15-billion-gallons corn-starch RFS.

In its final RFS ruling in 2010, EPA determined that corn-based ethanol from new plants meets the 20% GHG reduction criterion. The remaining fuels to meet the mandate must come from advanced biofuels that may be from either cellulosic or non-cellulosic sources. Advanced biofuels must be produced from a feedstock other than corn and achieve a 50% reduction in GHG emissions compared to conventional gasoline. Cellulosic advanced biofuels must be produced from any cellulose, hemicelluloses, or lignin from biomass and achieve a 60% reduction in GHG emissions compared to conventional gasoline. The emission reduction requirements may be reduced by 10% by the U.S. EPA should the initial reduction requirement not be feasible.[109] However, in its final 2010 ruling, EPA determined that all the biofuels it evaluated meet the GHG thresholds. Imported ethanol produced from sugarcane in Brazil, which is subject to approximately a $0.59 per gallon tariff (including a $0.54 most-favored nation duty and a 2.5% value-added tariff), may also be used for the other advanced biofuels category.

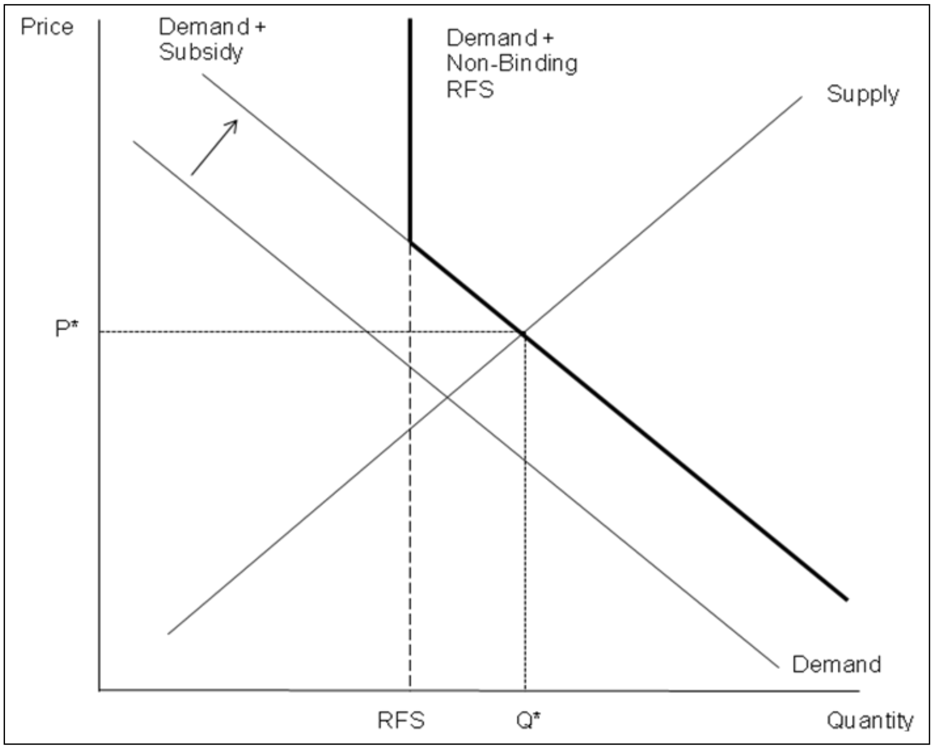
The RFS can be either non-binding or binding relative to the amount of biofuel that the market would otherwise demand. However, the two possible RFS scenarios generate very different market effects. The presence of the RFS will cause some portion of the demand curve to become vertical (as shown by the bold line in the following figures), and the effect of the RFS on the quantity and price will depend on how the RFS quantity compares to the quantity that would otherwise be demanded by the market. A non-binding RFS (**Figure 15**) will not affect the quantity or price, because the amount required by the RFS is below the market equilibrium. That is, the market is producing and consuming more ethanol than the RFS requires. However, a binding RFS (**Figure 16**) will have an effect on the quantity and price. When the RFS is binding, the market equilibrium quantity will be less than the RFS requires. Therefore, the RFS will cause the quantity of ethanol consumed and the ethanol price to increase.

The government mandate on the use of biofuels creates demand and is intended to encourage investment in improved technology and new plants. Supporters of the RFS contend that the policy helps to reduce investment risk by guaranteeing demand over the years that the RFS is in place, increases energy security, reduces dependence on imported oil, and offers environmental benefits by requiring the use of renewable resources for energy production. Critics of the RFS view the policy as potentially hindering the development of other alternative energy technologies since it strictly promotes renewable fuels, while a technology neutral policy such as a cap-and-trade system or a carbon tax would promote the development of multiple renewable energy technologies.[110]

[109] Section 202(c) of EISA, 2007 (P.L. 110-140), as codified in 42 U.S.C. 7545(o)(4).

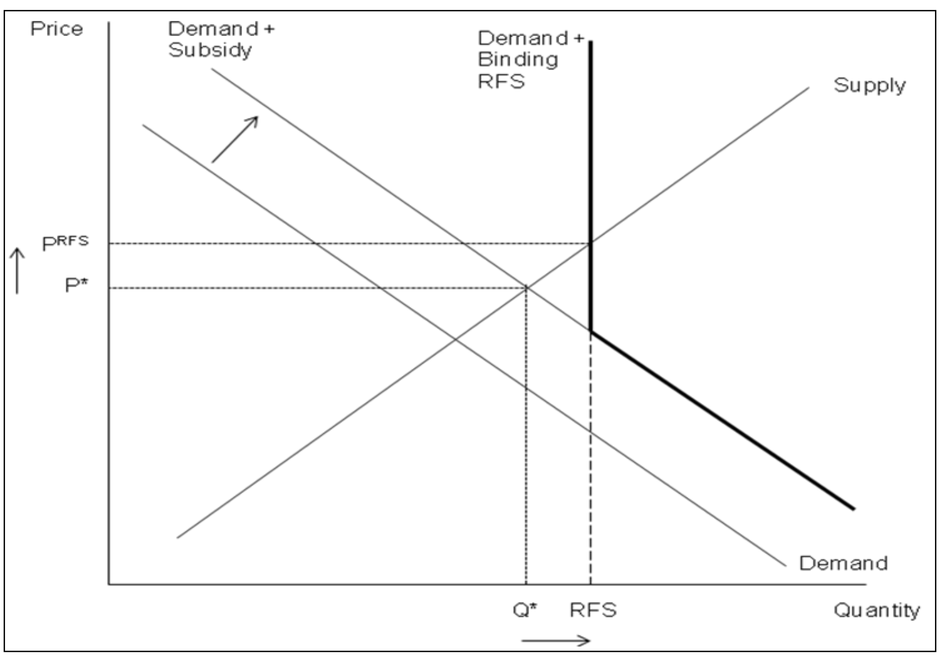
[110] CRS Report R40155, *Renewable Fuel Standard (RFS): Overview and Issues*, by Randy Schnepf and Brent D. Yacobucci.

Figure 15. Ethanol Subsidies and Non-Binding RFS



Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Figure 16. Ethanol Subsidies and Binding RFS



Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

The RFS as it stands is based on renewable fuel use at specific levels rather than renewable fuel use as a share of overall fuel use. Therefore, improvements in fuel efficiency that have been mandated by the federal government may make meeting the RFS more of a challenge. With improved fuel efficiency, less fuel is necessary to travel a given distance. The Energy Information Administration forecasts U.S. motor gasoline consumption to fall from about 138 billion gallons in 2009 to 122 billion in 2022.[111] Therefore the 36 billion gallon RFS will rise from a 26% share to a 30% share of gasoline consumption on a volumetric basis.

In its final RFS ruling in 2010, the EPA effectively converted the RFS from a volumetric basis to an energy basis. EPA interpreted the RFS as 36 billion gallons of ethanol equivalent by 2022. A gallon of bio-gasoline, with 50% more energy than ethanol counts as 1.5 gallons of ethanol equivalent. The EU 2020 target is energy equivalent as well.[112] That is, 20% of the energy content of liquid fuels must be renewable. That approach is technology neutral with respect to renewable liquid transportation fuels in that it leaves it entirely up to the market place to determine the fuels that will be produced (subject to environmental constraints).

Biomass Crop Assistance Program

The Biomass Crop Assistance Program (BCAP) was established in the Food, Conservation, and Energy Act of 2008 (2008 farm bill; P.L. 110-246) to encourage biomass production by providing financial assistance with crop establishment, collection, harvest, storage, and transportation costs, as well as annual payments for biomass production, to producers within an economically practical distance from a biomass facility.[113] As of August 2010, an estimated total of $243 million has been paid out to BCAP participants.[114] Producers who sell biomass to qualified biomass conversion facilities can expect to receive up to 75% of the cost of establishing and planting eligible biomass crops.[115] Matching funds are expected to be available for collection, harvest, storage, and transportation to a biomass conversion facility. The maximum government payment is $45/ton.[116] Applications are being accepted for conversion facilities to qualify for the program. Plants that have qualified for the program are from a variety of geographic locations and are using a variety of biomass feedstocks. The Supplemental Appropriations Act of 2010 (P.L. 111-212) limits mandatory spending on BCAP by allowing no more than $552 million in FY2010 and $432 million in FY2011; while no limit was placed on FY2012 funding.[117]

Fixed Subsidies

Federal subsidies in the form of an ethanol tax credit were first introduced in the Energy Tax Act of 1978. The tax credit has remained between 40 and 60 cents per gallon since then.[118] Previously, this subsidy was a volumetric ethanol excise tax credit. In 2004, it was changed to a blender's tax

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[111] U.S. Energy Information Administration, *Updated Annual Energy Outlook 2009*, Department of Energy, September 21, 2009; at [www.eia.doe.gov].

[112] Tyner, W.E., "The Integration of Energy and Agricultural Markets," *International Association of Agricultural Economics Annual Meeting 2009*, (Beijing, China).

[113] CRS Report R40110, *Biofuels Incentives: A Summary of Federal Programs*, by Brent D. Yacobucci.

[114] CRS Report R41296, *Biomass Crop Assistance Program (BCAP): Status and Issues*, by Megan Stubbs.

[115] Austin, A., "USDA's List of BCAP Qualifiers Grows," *Biomass Magazine*, September2 009.

[116] Grooms, L., "Fiber Farming Comes of Age," *Corn and Soybean Digest*, August2009.

[117] CRS Report R41296, *Biomass Crop Assistance Program (BCAP): Status and Issues*, by Megan Stubbs.

[118] Tyner, *Biofuels Origins and Prospects*, (2008).

credit, and is paid to the blender of the biofuel. The 2008 farm bill (P.L. 110-246) extended the blender's tax credit through 2010 but reduced it from $0.51 to $0.45 per gallon effective January 2009.

In addition to the $0.45 per gallon, there is a small ethanol producer credit of $0.10 per gallon for the first 15 million gallons produced each year by a small producer. Producers eligible for this credit must have an annual production capacity that is less than 60 million gallons.[119] About 1.6 billion gallons of ethanol applied for the small producer's tax credit in 2008. This credit is slated to last until the end of 2010.[120]

The 2008 farm bill also created a tax credit of $1.01 per gallon for producers of cellulosic biofuels.[121] Cellulosic ethanol that is also eligible for the volumetric ethanol excise tax credit, the small ethanol producer credit, or any other credit will only receive a total credit of $1.01 per gallon. This credit is set to expire at the end of 2012.

Variable Subsidies

The rapid increase in U.S. ethanol production (**Figure 10**) since 2005 has led to a concomitant increase in federal costs in the form of foregone revenue via the various tax credits (i.e., the fixed subsidies mentioned above). In 2009 the various fixed subsidies for biofuels in the United States cost nearly $5.9 billion, and is projected to reach at least $27 billion by 2022 if all tax credits are extended alongside of the RFS.[122] The biofuels tax credits have been available even during periods of extreme profitability such as occurred during 2006 and 2007. The high federal costs associated with the tax credits, coupled with the outlook for rapid growth in the cost of the fixed subsidy, have generated some interest among economists and federal budget watchdogs in favor of substituting a variable subsidy in place of the fixed subsidy as a means of lowering government costs while maintaining support for the biofuels industry.[123]

Unlike a fixed subsidy which remains constant in spite of market conditions, a variable subsidy adjusts its value depending on the current price of a barrel of oil. At high oil prices, above a certain threshold level, no subsidy is available, but as oil prices fall to the threshold level and then below, the variable subsidy kicks in and increases in value. Therefore, the subsidy amount paid is not constant as it is with a fixed subsidy.

In other words, a variable subsidy is designed to take into consideration the linkage between the ethanol industry's profitability and petroleum prices. In the absence of a blend wall, profitability of biofuel production will depend largely on the price of gasoline (which is highly correlated with oil prices), the primary commodity with which biofuels will compete. When oil and gasoline prices are high, biofuels are able to compete and remain profitable, while low oil prices make it difficult for biofuels to compete. Fixed subsidies ignore these differences. Fixed subsidies simply add to a plant's profitability, regardless of whether or not the plant would be profitable without

[119] CRS Report R40110, *Biofuels Incentives: A Summary of Federal Programs*, by Brent D. Yacobucci.

[120] CRS Report R41282, *Agriculture-Based Biofuels: Overview and Emerging Issues*, by Randy Schnepf.

[121] CRS Report R40110, *Biofuels Incentives: A Summary of Federal Programs*, by Brent D. Yacobucci.

[122] CRS Report R41282, *Agriculture-Based Biofuels: Overview and Emerging Issues*, by Randy Schnepf

[123] Tyner, Taheripour, and Perkis (2010); Tyner, W.E. and J. Quear, "Comparison of A Fixed and Variable Corn Ethanol Subsidy," *Choices* 21(3), 2006, pp. 199-202; Tyner, W.E. and F. Taheripour, "Renewable Energy Policy Alternatives for the Future," *American Journal of Agricultural Economics*, 89(5), 2007, pp. 1303-1310; and Tyner, W.E. and F. Taheripour, "Policy Options for Integrated Energy and Agricultural Markets," *Review of Agricultural Economics*, 30(3), 2008, pp. 387-396.

the subsidy. In contrast, variable subsidies change as oil prices change. A variable subsidy can reduce overall government costs since large subsidy amounts will not be paid all the time, but only when the oil price warrants in order for biofuels to be competitive.

Variable subsidies could be linked to either oil or gasoline prices, but it is expected that the difference between the two would be minimal considering the strong statistical relationship between oil and gasoline prices.[124] In designing a variable subsidy, an oil price where subsidies start must be chosen. This is often referred to as a trigger price or a cut off price. The rate of change must also be determined, such that for every dollar that the oil price falls below the cut off oil price, the subsidy will increase by the rate of change. Variable subsidies can be calculated given the average oil price on a monthly or quarterly basis. Generally, the variable subsidy would provide a safety net for biofuels producers when oil prices are low and allows the market to drive biofuels production without government intervention when oil prices are high. A recent analysis of the variable subsidy with respect to corn-based ethanol production found that the variable subsidy provides a net present value (NPV) for the producer that is similar to that with the fixed subsidy, but that the variable subsidy could decrease risk and the probability of a loss on investment.[125]

Analytical Comparison of Fixed and Variable Tax Credits

The remainder of this chapter will evaluate the impacts on ethanol producing firms of a variable versus a fixed tax-credit subsidy. This comparison is made, not as a policy recommendation, but (in response to widespread news and media coverage) strictly as a comparative analysis to aid Congress' understanding of the differences between the two policy options.

Note on Volumetric Pricing (VP) versus Energy-Equivalent Pricing (EEP)

The price of ethanol can be compared to gasoline on either an energy-equivalent basis or a volumetric basis. The choice is crucial because the two methods lead to different results due to the lower energy content of ethanol—the energy from a gallon of ethanol (measured in Btu's) is only about 67% of the energy content of a gallon of gasoline. Thus, on a volumetric basis the price of a gallon of ethanol is deemed equivalent to the price of a gallon of gasoline, but on an energy-equivalent basis the ethanol price equals only about 67% of the gasoline price.

Historically, since ethanol has been blended at very low rates (2% to 3%) with gasoline their prices have been linked primarily on a volumetric basis (**Figure 11**). In the near term volumetric pricing might work for the low level blends such as E10 or E15. However, as the ethanol blending share increases in the future it will likely be linked more on an energy basis. For example, consider the 85% blending rate implied by E85. Since E85 is expected to get 22% lower mileage than E10 (based on energy content), presumably consumers would only be willing to pay for E85 about 78% of the price of E10.[126]

Thermochemically-produced biofuels are nearly energy-equivalent to petroleum products (unlike biochemically-produced biofuels with a 67%-equivalency rate). As a result, the following analysis will consider cases in which biofuels produced by thermochemical methods receive a subsidy 49% greater than ethanol when calculated on an energy-equivalent basis.

[124] Tyner, Taheripour, and Perkis (2010).

[125] Ibid.

[126] Tyner, Dooley, and Viteri, (2010).

Profitability Model with Uncertainty

A spreadsheet model is used to evaluate the impacts of a fixed versus a variable (tax credit) subsidy on grain and cellulosic biofuels under three different processing technologies: the traditional corn-starch-to-ethanol process, as well as both biochemical and thermochemical processing of cellulosic biomass. In addition to the different subsidy schemes and processing technologies, the spreadsheet model also incorporates risk and uncertainty with respect to oil prices, natural gas prices, corn prices, and biomass prices.[127]

The model assumes that the life of the biofuel plant will be 22 years total with 2 years for construction and 20 years of operation. The profitability of biochemical and thermochemical cellulosic biofuel production processes are compared to corn-based ethanol production by calculating the net present values (NPVs) per gallon.

For this analysis, some parameters from the original model (Rismiller and Tyner (2009)) have been made stochastic in order to incorporate risk and uncertainty. Stochasticity is incorporated using @Risk, an add-in to Excel that runs Monte Carlo simulations to choose input parameters within a specified distribution, and then uses the results of the calculations from each draw from input distributions to produce output distributions, rather than single values, for the NPV of plants using different biofuel production processes. In this case, a simulation with 10,000 iterations is run and a random draw from each input distribution is used to calculate the output value. Once the simulation is complete, the mean and standard deviation of the outputs are calculated based on the results from all iterations.

Below is a brief description of how each parameter was altered. Unless otherwise stated, all amounts are adjusted to 2010 real dollars.

Oil Prices: A simple mean-reverting forecast[128] is used to approximate the low, middle, and high forecasts of oil prices from the 2010 DOE *Annual Energy Outlook*.[129] Each set of forecasts has a deterministic mean-reverting component as well as a random component for each year. The price volatility introduced by the random component provides a testing ground for the stated benefits of the variable subsidy. The oil price forecasts are illustrated in **Figure 17**.

Natural Gas Prices: Moving into 2010, the link between natural gas prices and oil prices appeared to have become weaker as new sources of natural gas were discovered in the United States.[130] The natural gas price is a random draw each year and is not linked to the previous year's price. The mean of $5.34 and the standard deviation of $0.92 was based on the monthly industrial price for natural gas from June 2009 to May 2010 and was used to create the distribution from which the natural gas price was drawn. The minimum natural gas price is $3 per thousand cubic feet, and the maximum natural gas price is $15 per thousand cubic feet, which are close to the recent historical minimum and maximum.

Corn Prices: The corn price is specified as a function of the oil price given the link between energy and agricultural prices that has arisen in recent years.[131] When done this way, a different corn price will be used each year as a function of the stochastic oil price described above and a random component. The stochastic oil price for each year is plugged into the following regression of corn prices on oil prices:[132]

Corn price = 1.78 + 0.029 * (*oil price*) + *eo* (where *eo* is a random normal error)

Regardless of how the corn price is calculated, the minimum corn price is $1.50 per bushel and the maximum corn price is $7.00 per bushel, which are close to the recent historical minimum and maximum.

DDGS Prices: The price of Distiller's Dried Grains and Solubles (DDGS) determines the revenue received by the corn-based ethanol plant for selling DDGS as a by-product. This price is calculated as a function of the corn price with the following equation:[133]

DDGS price = 38.27 + 22.77 * (*corn price*) + *ec* (where *ec* is a random normal error)

Gasoline Price: The gasoline price is calculated as a function of the stochastic oil price:

[127] The initial spreadsheet model (done in EXCEL) first appeared in Rismiller and Tyner (2009), but has been modified by D. Perkis of Purdue University for use in this report.

[128] This forecasting methodology is outlined in Tyner, Taheripour, and Perkis (2010).

[129] U.S. Energy Information Administration, *Annual Energy Outlook 2010 Early Release Overview*, Dept of Energy (Washington, DC.), 2010.

[130] Tyner, Taheripour, and Perkis (2010).

[131] Tyner, W.E., "The Integration of Energy and Agricultural Markets," *Agricultural Economics*, 41(6), 2010.

[132] From a working model by two of this report's authors, Perkis and Tyner.

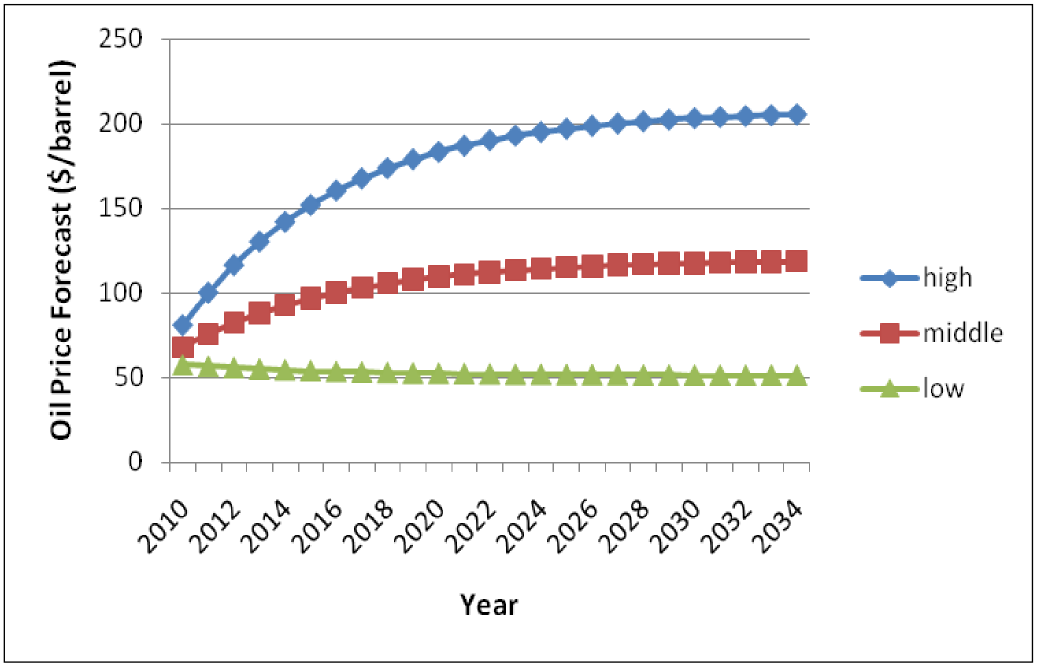
[133] Tyner, Taheripour, and Perkis (2010).

$$\textit{Gasoline price} = 0.35 + 0.023 * (\textit{oil price}) + \textit{eg} \qquad \text{(where } \textit{eg} \text{ is a random normal error)}$$

Using the stochastic oil price results in a different gasoline price each year.

Ethanol Price: Subsidies for ethanol blending and cellulosic biofuel production could be either fixed or variable. A fixed subsidy will be a per-gallon amount, while a variable subsidy will depend on a threshold oil price and a rate of change in the subsidy for each dollar below the threshold oil price that the market oil price falls. Current policy has cellulosic biofuel subsidies fixed on a volumetric basis ($1.01/gallon regardless of what biofuel is produced); for comparative purposes they will also be tested using an energy-equivalent basis.

Figure 17. Mean Oil Price Forecasts for Stochastic Simulations (2008 real dollars)



Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Breakeven Oil Prices

The breakeven oil price represents the price for oil at which the plant's net present value (NPV) is zero. At higher oil prices the plant operates with a positive NPV (i.e., the plant operates at a profit); at lower oil prices the plant operates with a negative NPV (i.e., at a loss). Breakeven oil prices are calculated for both volumetric and energy-equivalent biofuels pricing methods (and with and without fixed subsidies) for all three processing technologies (**Table 20**).

When ethanol is priced on a volumetric basis relative to gasoline, grain-based ethanol and biochemical conversion have lower breakeven oil prices than thermochemical conversion, both with and without the fixed subsidy. When biofuels are priced on an energy-equivalent basis, the price of a gallon of ethanol will be 67% of the price of a gallon of gasoline, rather than equal to the price of gasoline as it is under volumetric pricing. As a result, on an energy-equivalent pricing basis the breakeven oil prices for grain-based ethanol and biochemical conversion increase, while the breakeven oil price for thermochemical remains unchanged. Thus, thermochemical conversion has a better chance of competing with grain-based and biochemical ethanol under energy-equivalent pricing.

With a fixed subsidy included when calculating the plant NPV, the breakeven oil price declines in all cases (assuming that the subsidy is fully passed on to the biofuel producer, which will not always be the case). Ethanol pricing decisions do not affect thermochemical conversion. However, an energy-equivalent subsidy which takes into account the thermochemical product's higher energy rating in comparison to ethanol would make the thermochemical product competitive with both ethanol options.

Table 20. Breakeven Oil Prices ($/barrel)

			Thermochemical	
	Grain	**Biochemical**	**VP**	**EEP**
Volumetric Pricing (VP)				
Without Fixed Subsidies	$71.45	$126.68	$143.92	$143.92
With Fixed Subsidies[a]	$56.33	$92.74	$113.77	$98.92
Energy-Equivalent Pricing (EEP)				
Without Fixed Subsidies	$114.19	$196.64	$143.92	$143.92
With Fixed Subsidies	$91.62	$145.98	$113.77	$98.92

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Note: VP = volumetric biofuels pricing; EEP = energy-equivalent biofuels pricing. The breakeven oil price is indicated for the deterministic case (i.e., without incorporating any of the stochastics described in the text). All commodities are assumed to be at current market prices except for gasoline and ethanol. Gasoline is priced based on the relationship provided in the text (without the random error) and ethanol prices are linked to gasoline by volume or energy equivalency.

a. The fixed subsidies are $0.45 per gallon and $1.01 per gallon for ethanol and cellulosic, respectively, based on current legislation.

Profitability Results: Deterministic Case

The deterministic model is used to evaluate the profitability of biofuels production under both volumetric and energy-equivalent pricing methods but using current market prices for oil rather than the range of high, middle, and low from the previous section (**Table 21**). Grain and biochemical conversion do best when ethanol is priced on a volumetric basis relative to gasoline (primarily because they avoid the discount penalty related to lower energy content). However, only grain ethanol shows profitability even under volumetric pricing conditions.

Subsidies given for biofuels made from cellulosic biomass are currently done on a volumetric basis. Whether cellulosic biomass is used to produce a gallon of ethanol through biochemical conversion or a gallon of gasoline through thermochemical conversion, both receive a fixed subsidy of $1.01 per gallon. It is uncertain whether pricing and subsidies will change in the future to an energy-equivalent basis.

Table 21. Profitability (NPV) with Fixed Subsidies, Deterministic Case

			Thermochemical	
	Grain	**Biochemical**	**VP**	**EEP**
		$ per gallon of annual capacity		
Volumetric Pricing (VP)	$2.32	**-$2.51**	**-$5.42**	**-$3.41**
Energy-Equivalent Pricing (EEP)	**-$1.58**	**-$6.42**	**-$5.42**	**-$3.41**

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Note: Negative values are in bold. VP = volumetric biofuels pricing; EEP = energy-equivalent biofuels pricing.

Profitability Results: Stochastic Case

Variable Subsidy Defined

Stochastic model simulations are adopted to evaluate the variable subsidy whose per-unit value changes as market conditions change. A variable subsidy functions by providing firms with more support at low oil prices and withdrawing the subsidy at higher oil prices. The hypothetical variable subsidy evaluated in this analysis is based on a $90 per barrel oil price threshold and a $0.02 per gallon increment in additional subsidy for each dollar that the oil price is below the cut off. The following table (**Table 22**) shows variable subsidy rates at different oil market prices.

Table 22. Hypothetical Variable Biofuel Subsidy Under Various Oil Price Scenarios

Market price of oil ($/barrel)	Variable Subsidy ($ per gallon of biofuel)
$110	$0.00
$100	$0.00
$90 (threshold)	$0.00
$85	$0.10
$80	$0.20
$75	$0.30
$70	$0.40
$60	$0.60

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

The net effect of replacing a fixed subsidy with a variable subsidy is that, while firms decrease their chances of operating at a loss, and government subsidies are reduced, there can be a slight drop in NPV compared to the fixed subsidy because no subsidy is paid out when the price of oil is $90 or higher. Thus, if profits for the various processing technologies are negative under a fixed subsidy across several potential oil price forecasts, then it is likely that the technology will not be profitable with a variable subsidy either. More research is needed to define a variable subsidy structure that works well for cellulosic biofuels.

Stochastic Baseline

To provide a baseline for profitability under stochastic conditions, **Table 23**, **Table 24**, and **Table 25** provide the stochastic means and standard deviations for the net present value (NPV), the probability of a loss, and the coefficient of variation with a fixed subsidy for each of the three oil price forecast scenarios: low, medium, and high oil price forecasts, respectively. Because different annual production capacities area assumed for each of the technologies (100 MGPY for corn ethanol and 50 MGPY otherwise), all NPV are expressed in per-gallons-of-annual-capacity to facilitate comparison.

In addition to NPV comparisons demonstrating profitability across different scenarios, these three tables include data to facilitate a comparison of the per-gallon-of-capacity **Subsidy Cost** (i.e., the tax revenue foregone by the tax credit), the new **Tax Revenue** (equal to the fuel tax revenue obtained from producing new biofuels), and the **Net Government Cost** (which equals the

Subsidy Cost minus the **Tax Revenue**). Each government measure is also expressed as a NPV per gallon of annual capacity.

In general, all three of the technologies show positive profits with a high degree of probability when high oil prices are forecast, due primarily to higher oil-induced revenues. But profitability drops off at lower oil price forecasts, and as energy-equivalent pricing is adopted for biochemical processing and volumetric pricing for thermochemical processing. Note that the fixed subsidy cost shows no variability across the different oil price forecasts since payments are made for each gallon without respect to market conditions.

Under a scenario of low forecast oil prices and a fixed subsidy, only grain ethanol with volumetric pricing is profitable (**Table 23**). This is perhaps most representative of the biofuels industry's current situation since cash oil prices in the mid-$70s are presently closest to the levels of the low oil price forecast case.

As oil price forecasts increase, ethanol and biofuels priced to compete with oil and gasoline should command more revenue and become more profitable. The middle oil price forecast scenario confirms this (**Table 24**). Note however that the standard deviation in NPV does not allow for definitively ruling out negative profits in most cases (i.e., NPV minus its standard deviation < 0), even when NPV's are positive.

Only grain ethanol priced volumetrically has an NPV large enough to ensure profits in most cases (99.4% of the time). If oil prices follow the high-level forecast, most alternative biofuel technologies will be profitable with a high probability due to higher oil-induced revenues (**Table 25**).

Table 23. Profitability with Fixed Subsidies at Low Oil Price Forecasts

	——-Grain——-		—-Biochemical—-		— Thermochemical—	
	VP	**EEP**	**VP**	**EEP**	**VP**	**EEP**
NPV ($/gallon of capacity)	$1.43	**-$1.63**	**-$5.08**	**-$8.14**	**-$7.99**	**-$5.98**
(NPV standard deviation)	($1.16)	($0.58)	($2.45)	($2.03)	($2.60)	($2.61)
Probability of a Loss (%)	11.1%	99.7%	98.4%	100.0%	100.0%	98.9%
Coefficient of Variation	0.81	**-0.36**	**-0.48**	**-0.25**	**-0.33**	**-0.44**
Subsidy Cost	$2.68	$2.68	$6.01	$6.01	$6.01	$8.98
Tax Revenue (TR)	$0.59	**-$0.43**	**-$1.28**	**-$2.30**	**-$1.99**	**-$1.32**
(TR standard deviation)	($0.39)	($0.19)	($0.82)	($0.60)	($0.87)	($0.87)
Net Govt. Cost (NGC)	$2.08	$3.11	$7.29	$8.31	$8.01	$10.30
(NGC standard deviation)	($0.39)	($0.19)	($0.82)	($0.68)	($0.87)	($0.87)

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Notes: All prices are expressed in per-gallon-of-annual-capacity to facilitate comparison across different plant sizes. NPV = Net Present Value. Negative values are in bold. VP = volumetric biofuels pricing; EEP = energy-equivalent biofuels pricing. The standard deviation is a statistical measure of deviation around the mean value. The Coefficient of Variation (CV) is the ratio of the standard deviation over the mean value. The CV is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other.

Table 24. Profitability with Fixed Subsidies at Middle Oil Price Forecasts

	——-Grain——-		—Biochemical—		—Thermochemical—	
	VP	**EEP**	**VP**	**EEP**	**VP**	**EEP**
NPV ($/gallon of capacity)	$5.76	$0.42	$1.81	**-$3.53**	**-$1.43**	$0.58
(NPV standard deviation)	($2.78)	($1.39)	($4.56)	($3.26)	($4.58)	($4.55)
Probability of a Loss (%)	0.6%	40.9%	36.2%	85.9%	62.9%	46.4%
Coefficient of Variation	0.48	3.31	2.52	**-0.92**	**-3.20**	7.84
Subsidy Cost	$2.68	$2.68	$6.01	$6.01	$6.01	$8.98
Tax Revenue (TR)	$2.04	$0.26	$1.02	**-$0.76**	$0.20	$0.86
(TR standard deviation)	($0.93)	($0.46)	($1.52)	($1.09)	($1.53)	($1.52)
Net Govt. Cost (NGC)	$0.64	$2.42	$5.00	$6.78	$5.82	$8.11
(NGC standard deviation)	($0.93)	($0.46)	($1.52)	($1.09)	($1.53)	($1.52)

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Notes: See notes for Table 23.

Table 25. Profitability with Fixed Subsidies at High Oil Price Forecasts

	——-Grain——-		—Biochemical—		—Thermochemical—	
	VP	**EEP**	**VP**	**EEP**	**VP**	**EEP**
NPV ($/gallon of capacity)	$12.73	$4.48	$10.63	$2.40	$7.01	$9.04
(NPV standard deviation)	($5.61)	($3.29)	($7.15)	($4.89)	($7.09)	($7.02)
Probability of a Loss (%)	0.02%	6.3%	6.8%	32.2%	17.2%	10.0%
Coefficient of Variation	0.44	0.73	0.67	2.04	1.01	0.78
Subsidy Cost	$2.68	$2.68	$6.01	$6.01	$6.01	$8.98
Tax Revenue (TR)	$4.36	$1.61	$3.96	$1.21	$3.01	$3.69
(TR standard deviation)	($1.87)	($1.10)	($2.38)	($1.63)	($2.36)	($2.34)
Net Govt. Cost (NGC)	**-$1.68**	$1.07	$2.06	$4.80	$3.01	$5.29
(NGC standard deviation)	($1.87)	($1.10)	($2.38)	($1.63)	($2.36)	($2.34)

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Notes: See notes for Table 23.

Stochastic Comparison of a Fixed versus a Variable Subsidy

Given the baseline implied by the previous three tables, it is only meaningful to compare a variable subsidy with a fixed subsidy when a technology shows the potential of being profitable in the fixed subsidy case. Since only grain ethanol was profitable across all oil price forecasts, it is the sole scenario used to compare the different effects of fixed and variable subsidies. Thus, considering only grain ethanol under volumetric pricing, and regardless of the oil price scenario, the standard deviation and the probability of a loss both decrease under a variable subsidy as compared to a fixed subsidy (**Table 26**) suggesting a clear risk-reducing effect.

Table 26. Profitability with Volumetric Pricing for Grain Ethanol, Stochastic Case

	Low Oil	**Middle Oil**	**High Oil**
Fixed Subsidy			
NPV ($/gallon of capacity)	$1.43	$5.76	$12.73
(NPV standard deviation)	($1.16)	($2.78)	($5.61)
Probability of a Loss	11.1%	0.6%	0.02%
Coefficient of Variation	0.81	0.48	0.44
Variable Subsidy			
NPV ($/gallon of capacity)	$1.09	$4.44	$11.09
(NPV standard deviation)	($0.50)	($2.24)	($5.26)
Probability of a Loss	0.5%	0.0%	0.0%
Coefficient of Variation	0.46	0.50	0.47

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Notes: See notes for Table 23.

In addition to reducing the risk of a loss to firms, it is clear that the government's costs are reduced regardless of the oil price outcome, and often to a considerable level (**Table 27**) under a variable subsidy.

Table 27. Subsidy Costs, Tax Revenues, and Net Government Costs with Volumetric Pricing for Grain Ethanol, Stochastic Case

	Low Oil	Middle Oil	High Oil
Fixed Subsidy	**NPV per gallon of capacity**		
Subsidy Cost	$2.68	$2.68	$2.68
Tax Revenue	$0.59 ($0.39)	$2.04 ($0.93)	$4.36 ($1.87)
Net Government Cost	$2.08 ($0.39)	$0.64 ($0.93)	**-$1.68** ($1.87)
Variable Subsidy	**NPV per gallon of capacity**		
Subsidy Cost	$2.23 ($1.31)	$0.91 ($1.10)	$0.51 ($0.77)
Tax Revenue	$0.48 ($0.17)	$1.60 ($0.75)	$3.82 ($1.75)
Net Government Cost	$1.75 ($1.35)	**-$0.68** ($1.63)	**-$3.31** ($2.25)

Source: Tyner, Brechbill, and Perkis, Purdue University, August 2010.

Notes: Standard deviations are in parentheses. Negative values are in bold.

Conclusions

In conclusion, when correctly designed, variable subsidies could reduce risk to firms by decreasing the standard deviation of the net present value. A variable subsidy should also reduce the cost to the government relative to a fixed subsidy, because the government will only subsidize a firm when the oil price is low enough to keep biofuels from being competitive with oil. Fixed subsidies, however, will be paid out regardless of the oil price and whether biofuels could be viable without the subsidy.

When biofuels are priced and subsidized on the basis of energy content, thermochemical conversion could be the least expensive – based on the assumptions in this study. When volumetric pricing of subsidies is used, the higher energy content of biofuels produced via thermochemical conversion will not be properly valued.

All the numeric conclusions in this section, of course, depend on the cost structures, pricing relationships, and other assumptions used in this study. All the numbers come from the literature, but there may be proprietary technologies in the wings with lower costs and/or higher conversion rates.

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